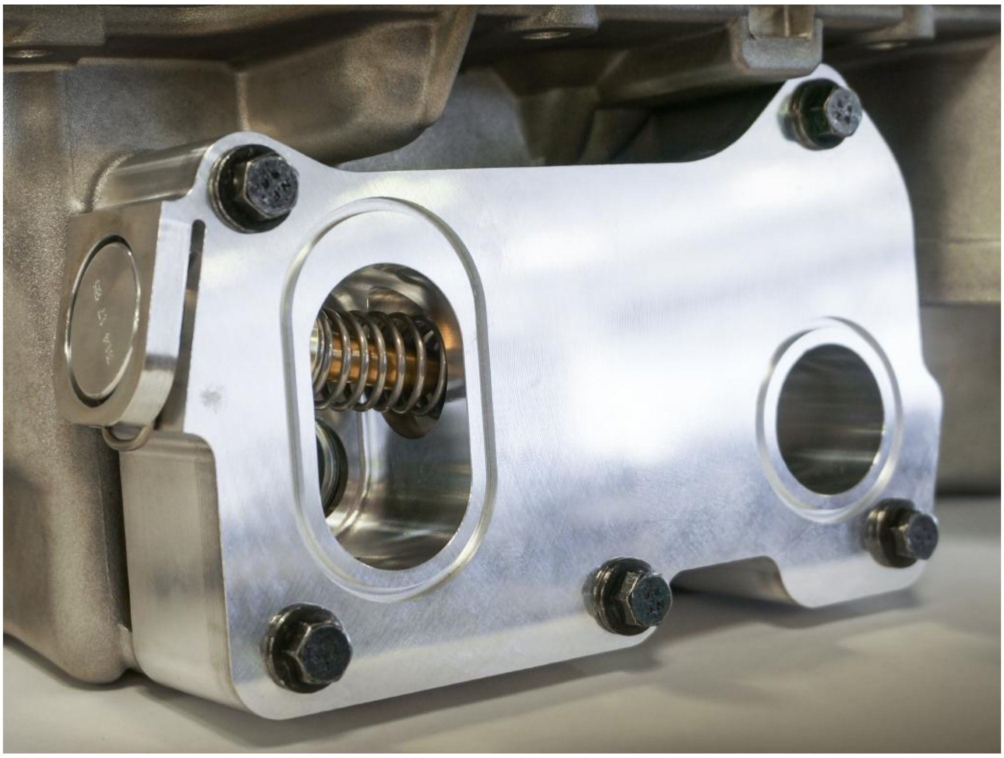
CHALMERS
UNIVERSITY OF TECHNOLOGY



Reducing Time-To-Pressure in Oil System of Combustion Engine with Oil Cooler

Investigation of bypassing the oil cooler in an internal combustion engine

Bachelor's Thesis in Mechanical Engineering

Axel Hellsten
Oskar Pettersson

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Bachelor's thesis 2018:48

Reducing Time-To-Pressure in Oil System of Combustion Engine with Oil Cooler

Investigation of bypassing the oil cooler
in an internal combustion engine

AXEL HELLSTEN, OSKAR PETTERSSON

Department of Mechanics and Maritime Sciences
Mechanical Engineering
Chalmers University of Technology
Gothenburg, Sweden 2018

Reducing Time-To-Pressure in Oil System of Combustion Engine with Oil Cooler
Investigation of bypassing the oil cooler in an internal combustion engine
Axel Hellsten, Oskar Pettersson

Supervisor: Daniel Arvidsson, Volvo Car Corporation
Examiner: Karin Munch, Department of Mechanics and Maritime Sciences

Thesis Work 2018:48
Department of Mechanics and Maritime Sciences
Mechanical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Adapter plate prototype.

Typeset in LaTeX
Gothenburg, Sweden 2018

Abstract

The time-to-pressure in the oil system of an internal combustion engine is important to ensure that all moving components in the engine gets the lubrication and cooling needed. If the time is too long the friction between moving parts will cause wear which in turn can lead to an engine breakdown. There is a large pressure drop over the oil cooler in VEA GEN3 which is one of the main causes for the long time-to-pressure during cold starts. The conditions when this issue occurs are very extreme with temperatures at -30 °C. During these very low temperatures the oil viscosity behaviour changes rapidly where small temperature variations make huge difference. This bachelor thesis aims to reduce the time-to-pressure by designing a a technical solution that bypasses the oil cooler.

The bypass valve has been developed from a conceptual phase into a functional prototype. By using different methods to create concepts and thereafter evaluate them, the project ended up with two concepts that were developed further. 3D models were created in CAD that were used to do CFD simulations later on. The calculated CFD-results of the pressure drop over the bypass valve were to be verified by producing a properly functional prototype. With the bypass prototype installed on an engine, in a cold climate chamber, measurements were done and compared to baseline runs.

The results of the CFD-simulations showed positive indications of a large reduction in pressure drop with the bypass installed. The simulation results were verified by real test results where time-to-pressure was reduced by 50% in comparison to the baseline engine. The project thereby accomplished the task to manage time-to-pressure below 4 seconds.

Keywords: Volvo Cars, combustion engine, oil system, bypass valve, oil pressure, time to pressure.

Sammanfattning

Tid till tryck i oljesystemet av en förbränningsmotor är viktigt för att säkerställa att alla rörliga komponenter i motorn får den smörjning och kylning som krävs. Om tiden är för lång kommer friktionen mellan de rörliga delarna generera slitage vilket i sin tur kan leda till ett motorhaveri. I Volvo Cars framtida motorserie VEA GEN3 har det upptäckts att för lång tid till tryck är ett problem vid kallstarter. Huvudorsaken är fastställd till att det är oljekylet med sitt stora tryckfall i kombination med extrema förhållanden där temperaturer kring -30 °C leder till för lång tid till tryck. Vid dessa låga temperaturer ändrar sig viskositetsegenskaperna snabbt där små temperaturvariationer har en stor påverkan på oljans strömning genom systemet. Målsättningen med detta examensarbete är att reducera tid till tryck genom att konstruera en teknisk lösning som leder oljan förbi oljekylet.

En förbikoppling, även kallad bypassventil, har utvecklats från ett konceptstadie till en fullt fungerande prototyp. Genom att använda olika metoder för att skapa koncept och därefter utvärdera dem resulterade projektet i två koncept som vidareutvecklades. 3D modeller skapades i CAD som senare användes till att göra CFD-simuleringar. Resultaten från flödessimuleringarna verifierades genom att tillverka en fungerande prototyp som monterades på en motor. Den kördes i en klimatkammare hos VCC där mätningar gjordes och som sedan jämfördes mot referensmotorn utan bypass.

Resultatet av CFD simuleringarna, med bypassventilen installerad, indikerade på stora reduktioner av tryckfallet. Simuleringarna visade sig korrelera väl mot resultaten från kallstartsproven då tid till tryck reducerades med 51% i jämförelse med referensmotorn utan bypass. Projektet lyckades därmed uppnå målet att reducera tid till tryck i oljesystemet under fyra sekunder.

Nyckelord: Volvo Cars, förbränningsmotor, oljesystem, bypassventil, oljetryck, tid till tryck.

Acknowledgements

This Bachelor's thesis was performed at the oil system group within the base engine department at Volvo Cars. We would like to thank our supervisor Daniel Arvidsson at Volvo Cars for his sharing of knowledge, mindset and guidance throughout this Bachelor thesis. We would also like to thank Jonatan Ekstrand for his challenging questions and knowledge sharing. It has been a great pleasure working with both of you.

We would also like to thank our examiner Karin Munch who in a straightforward manner has been guiding us through this Bachelor thesis.

Axel Hellsten & Oskar Pettersson, Gothenburg, June 2018

Contents

List of Figures

List of Tables

Notations

Abbreviations

CAE	Computer Aided Engineering
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
GEN3	Generation 3
ICE	Internal Combustion Engine
MBS	Mass Balancing System
NVH	Noise, Vibration and Harshness
RPM	Revolution Per Minute
RPN	Risk Priority Number
VCC	Volvo Car Corporation
VEA	Volvo Engine Architecture

Units

cc	Volume	[cm^2]
po	Pressure	[N/m^2]
Q	Flow Rate	[m^3/s]
$\triangle P$	Pressure difference	[Pa]
μ	Viscosity	[Ns/m^2]
R	Resistance	$\left[\frac{N/m^2}{m^3/sec}\right]$
t	Time	[sec]
V	Volume	[cm^2]
r	Radius	[mm]
L	Length of pipe	[mm]

1| Introduction

The legal regulations continuously set higher demands on the car manufacturers needing to decrease emissions from combustion engines. To fulfill these demands Volvo Cars chose to downsize their engine fleet to a new four cylinder engine back in 2013. Still, the customers demand high performance engines which creates a challenge for the engineers to control the more complex thermal management. Larger coolers contributes to higher pressure drops and creates problems when wanting to build up pressure. For this project the oil system is in focus and the issue is too long time-to-pressure occurring at cold starts.

1.1 Problem description

In the ongoing VEA GEN3 project there are existing difficulties to fulfill the requirements for time-to-pressure in the oil system when performing cold climate starts. The problem has shown to be too high oil pressure losses over the oil cooler due to it's large size and designed to optimize the cooling of the oil at high temperatures. When performing cold starts at -30°C the requirement is to have oil pressure higher than 100 kPa in the whole oil system after 4 seconds from initial start of the engine. The components with largest impact on the time-to-pressure, in terms of oil pressure losses, are the oil cooler and the oil filter.

1.2 Objective

The purpose of this assignment is to design a technical solution that bypasses the oil cooler at cold starts. The project aims to end up with conceptual drawings of a solution and a prototype for engine testing.

1.3 Solution

The bypass solution should not require any changes to the oil cooler itself, instead it is intended to be contained in the oil sump or as external parts. An overview of the oil system is displayed in figure 1.1. The bypass function needs to be evaluated and chosen. The solution should decrease the pressure drop as much as possible. It will be compared against the baseline with a pressure drop over the oil cooler that is measured to be 4 bar. To verify the bypass function, the time and pressure levels will be measured when performing tests with the baseline and bypass engine in a cold climate chamber.

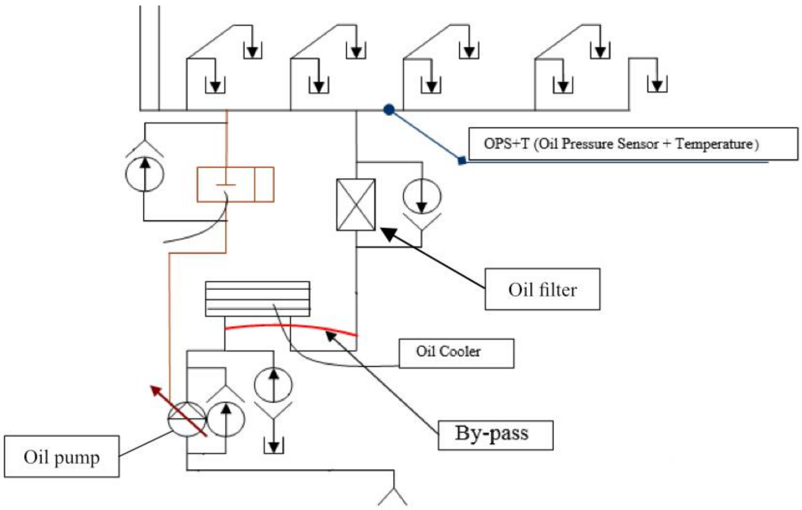


Figure 1.1: Schematic overview of the oil system with intended bypass marked in red.

1.4 Deliverables

In accordance with the aim of the project, the following points of research are to be investigated:

- Is it possible to reduce the time-to-pressure in the oil system with a bypass valve?
- Will the solution meet the requirement of time-to-pressure in the oil system within 4 seconds from start?
- Design a concept that includes a technical solution for future engines.

1.5 Limitations

Due to the design of the oil system a solution has to be implemented within the area of the oil pan and the oil cooler. There will not be any modifications made to the oil cooler for the reason that the part is developed by a supplier to VCC. The thermal management, regarding heating of the combustion engine, will not be investigated in this project.

2| Scope

2.1 Engine

Internal combustion engines have been used since the 19th century in various applications. The most common application for modern ICE is in the automotive industry, such as in cars, trucks and buses. The daily user has high demands and expectations regarding the function of the vehicle. The engine is a main function and required to always work in order to transport the persons and belongings in question. With tougher demands from global legal departments, regarding emissions, the car manufacturers are pushing the limits to deliver cars that meet the continuously updating requirements.

A strong trend among today's car manufacturers is downsizing, meaning that the engines are getting smaller regarding number of cylinders and displacement. The result is engines with better fuel economy and decreased emissions. One of the challenges for the engineers is to maintain performance that satisfies the customer. A smaller engine requires help from, for instance turbos, super chargers, and other high-tech components to reach the target power. Imagine that a small four cylinder engine shall deliver as much power as a five, six or even eight cylinder engine. The load will thereby increase on a smaller engine and with the maintained level of performance will naturally generate much more heat. The heating has to be controlled by using heat exchangers of various types. In the automotive industry, where space is limited, a plate heat exchanger is often used to cool the engine oil. A water coolant is used to cool the whole engine and keep it at a stable temperature. The coolant is often used to transport the heat from the oil plate heat exchanger and is afterwards cooled by the air-vent caused by the cars movement.

There is a lot of work put in to tune the cooling system of an engine and it is a vital function that always has to perform according to set requirements. Failure to do so could cause damage to the engine and in worst cases prevent the customer from using the car. When developing a brand new engine there are a lot of parameters to be taken into account. The engineers of a particular system can do calculations and virtual simulations to approximate the outcome. The history of development shows that the reality often can differ from the simulation and the most unexpected phenomena can occur. Therefor it is important to perform testing and to verify the functions when all systems are working together.

2.2 Oil system

The oil is used to lubricate and cool the moving parts in the engine. The oil system consists of a pump, a filter, a cooler, channels to transfer the oil and an oil pan. The general flow of the oil is shown in figure 2.1, most of the moving parts that need lubrication is located in the cylinder head and in the engine block. The oil pump pumps the oil through the oil cooler and then through the oil filter before it flows up through the engine.

The bypass solution researched in this project is meant to bypass the oil cooler, which is a water-to-oil heat exchanger. These coolers are common heat exchangers in the automotive industry due to a compact design and the ability to exchange heat with the water coolant and thus only needing one radiator instead of two. One downside is the low flow rate through a compact plate heat exchanger when having fluids with high viscosity.

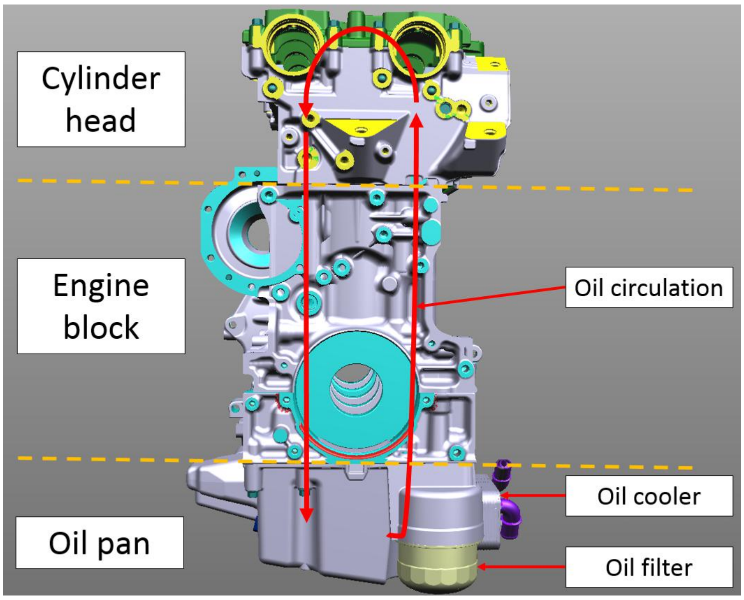


Figure 2.1: Illustrtion of the main parts of an engine with oil circulation.

2.3 Environmental conditions

Since the existing problem with long time-to-pressure only occurs at cold temperatures around -30°C, the recreation of the test environment is truly important. VCC has set a standard and the test conditions will resemble the real conditions with -30°C as the lowest temperature. There are different ways of creating these conditions, either putting an engine in a cold climate chamber, putting a complete vehicle in a cold climate chamber or bringing the complete vehicle to real nature with a climate that has the desired temperature.

2.4 Customer point of view

Both VCC and the costumer have the greatest interest in that the car always will start, no matter what the conditions are. In climates around -30°C it is critical for the engine to start in the first attempts, otherwise the battery may drain quickly and complications will occur. Regarding time-to-pressure there is a possibility to crank the engine during a longer time before igniting the fuel and thereby building enough oil pressure before starting the combustion cycle. The function can drain the battery as described above and cause irritation for the customer.

3| Theory

3.1 Oil pan

As shown in figure 2.1 the oil pan is located at the bottom of the engine. The oil pan is from where the oil is pumped into the oil channels of the engine and where it flows back to after it has reached all parts of the oil system (D. Arvidsson (Personal communication, May, 2018)). Almost all oil is collected in the oil pan when the engine is turned off, only small volumes are stuck in different cavities of the oil system.

The oil pan does not only function as a container for the oil and various components, it is also an important structural part of the engine (D. Arvidsson (Personal communication, May, 2018)). It has to withstand vibrations and loads created by the combustion process while always keeping the engine sealed, so that it does not leak any oil. The oil pan can be made in various materials but the most commonly used at VCC is aluminum. The benefits of it are the light weight and minor corrosion.

There are several components held within the compartment of the oil pan, the two main being the oil pump and the Mass Balancer System unit (D. Arvidsson (Personal communication, May, 2018)). The oil filter and the oil cooler are located on the outside of the oil pan. The volume of the oil contained in the oil pan is restricted by these components, the oil pan can not be altered too much because that will result in a different oil level than intended for the engine. There are also restrictions on the outside of the oil pan, such as the ground, the subframe of the car, electrical harnesses, pipes and hoses which limits the size of the oil pan.

3.2 Oil cooler

The oil cooler used in the VEA GEN3 engine is a water-to-oil plate heat exchanger. A plate heat exchanger holds the advantage over other heat exchangers that it has a large surface area over which the fluids can exchange heat, this makes the plate heat exchanger an efficient cooler. The plates are organized so that the two fluids exchanging heat flow through every other plate, maximizing the surface area between the fluids. The basic idea of how the plate heat exchanger work is shown in figure 3.1. The water used in the water-to-oil heat exchanger is the coolant for the engine. Using the coolant makes it possible to only have one radiator for both the oil- and the cooling system, which saves space in the engine bay. One of the drawbacks of the plate heat exchanger is the large surface area and the tight space between the palates, which creates a lot of friction. This leads to higher pressure drops over the plate heat exchangers in relation to other variants (Thermaxx, 2018).

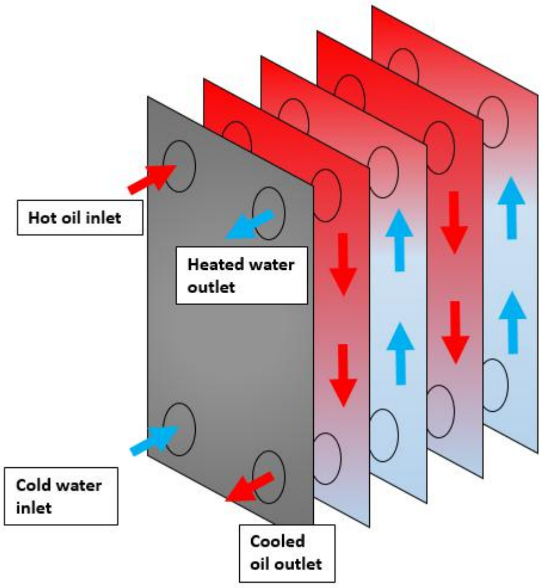


Figure 3.1: Principle of a plate heat exchanger.

3.3 Oil

The engine oil has various functions in the combustion engine. The main function is to lubricate and cool the moving parts in the engine, but the oil also removes grime in form of soot and particles from the inside of the engine (Pennzoil, 2018). The oil filter is intended to clean the oil so that it maintains proper lubrication properties (Exxon Mobil, 2018).

The viscosity of the engine oil increases in conjunction of decreasing temperature (White, 2011). The curve for SAE 10 oil in figure 3.2 shows how the viscosity exponentially grows already at 0°C. The oil supplier to VCC, Castrol, does not have exact data about the oil at such low temperatures as -30°C, though it is clear how general engine oil have an exponential growth of viscosity when becoming colder (White, 2011). The difference in viscosity at these low temperatures is an important factor contributing to the long time-to-pressure at cold starts. Due to the small channels between the plates of the oil cooler, the high viscosity at -30°C makes it difficult for the oil to pass through. In conjunction with the volume of the cooler that has to be filled up it generates the total pressure drop of the particular part.

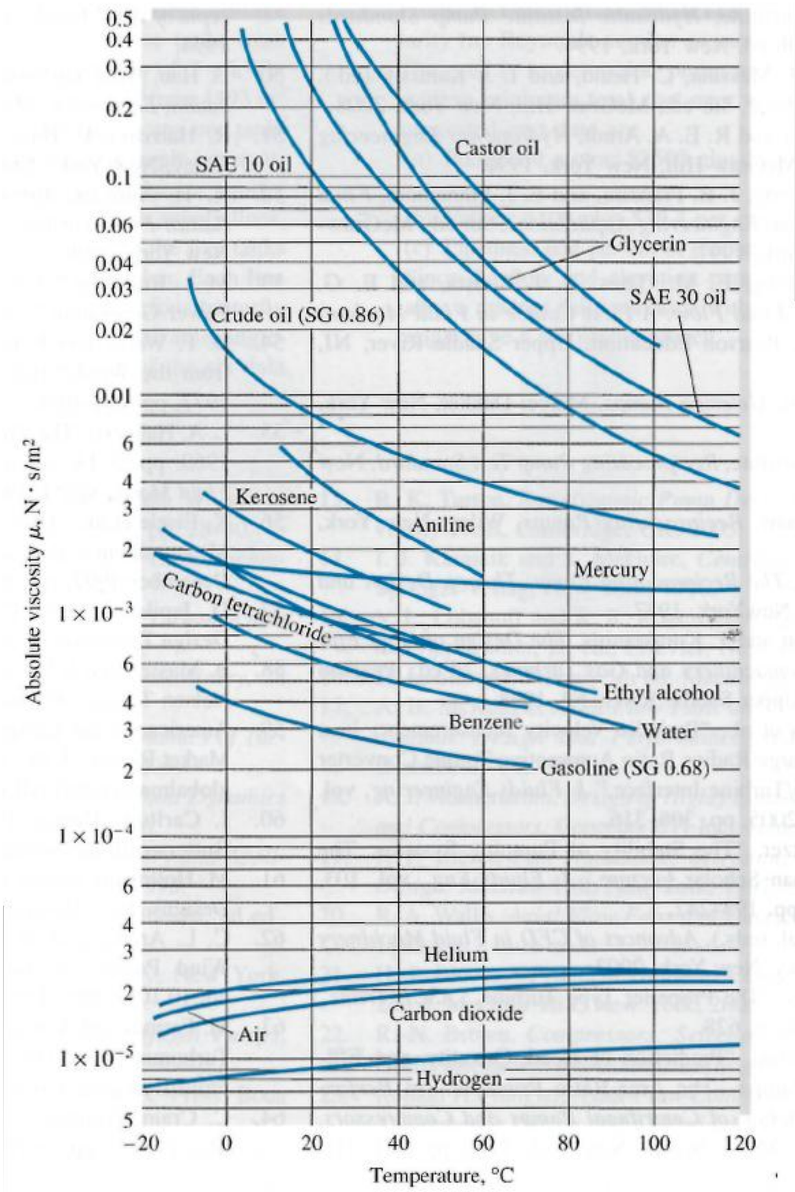


Figure 3.2: Absolute viscosity of common fluids at 1 atm. SAE 10 oil is common engine oil, (White, 2011).

3.4 Oil pump

The task of the oil pump is to pressurize the engine oil and to circulate it through the oil system. The oil pump in the VEA GEN3 engine is driven by the crankshaft and is thereby proportional to the engine RPM. The oil pump is variable to ensure that the pressure always is the same in the oil system, even though the speed of the oil pump varies. (D. Arvidsson (Personal communication, May, 2018))

3.5 Thermostat

A thermostat is a type of valve which can control fluid flow through different paths of a system based on current temperature (HowStuffWorks, 2018b). When the fluid reaches a certain predetermined temperature the thermostat will switch path for the fluid to flow. This mechanism is often used in the engine cooling systems of vehicles. Firstly the coolant will warm up until it is heated to correct temperature, secondly it will start flowing through a cooler (HowStuffWorks, 2018a).

The wax body is the part of the thermostat which reacts to temperature changes (HowStuffWorks, 2018b). When the surrounding fluid heats up the wax body the wax inside melts and expands. The expanding wax forces a pin outwards which moves the thermostat. The length of travel is the distance the body which contains the wax can move, from one dead end to the other. In order for the thermostat to work properly, the fluid which is regulated need to flow around the wax body. If there is no continuous flow around the wax body the thermostat will not sense the temperature difference as intended which can result in flawed function.

3.6 Solenoid

A solenoid primarily consists of a coil and a core, it operates by converting electrical energy to mechanical energy (Connexion Developments, 2018). When an electrical current is induced into the coil it creates a magnetic field which affects the core. The core is made from a magnetic material which reacts to the magnetic field created by the coil. The movement of the core caused by switching the current on or off is used when a valve is attached to open or close the valve.

In automotive applications the solenoid valve can be controlled by connecting it to the engine control unit of the car which has data from the sensors placed on the engine. Using the information provided from the sensors the computer can make decisions whether the solenoid should be opened or closed (D. Arvidsson (Personal communication, May, 2018).

3.7 Fluid Dynamics

Pressure difference, flow rates, resistances and time-to-pressure are dependent by the geometry of the oil system and the properties of the oil. The underlying theory of why a bypass in a pressurized system will function can be described with Poiseuilles law (White, 2011). The law considers the flow rate that is dependent by the pressure difference over the system and the internal resistance of the system. The higher the pressure drop, the higher potential of a large flow rate there is. The resistance however, has to be kept small if a large flow rate is desirable.

$$Q = \frac{\triangle P}{R} \tag{3.1}$$

The resistance is dependent by the viscosity of the fluid, the length of the pipe and it's inner radius.

$$R = \frac{8\mu L}{\pi r^4} \tag{3.2}$$

In figure 3.3 a schematic view shows the two possible routes for the oil to flow. To achieve the desired function of the bypass valve it should have a lower resistance than the part that is to be bypassed. When so is the case a higher flow rate will pass through the bypass valve, thereby pressurizing the system quicker.

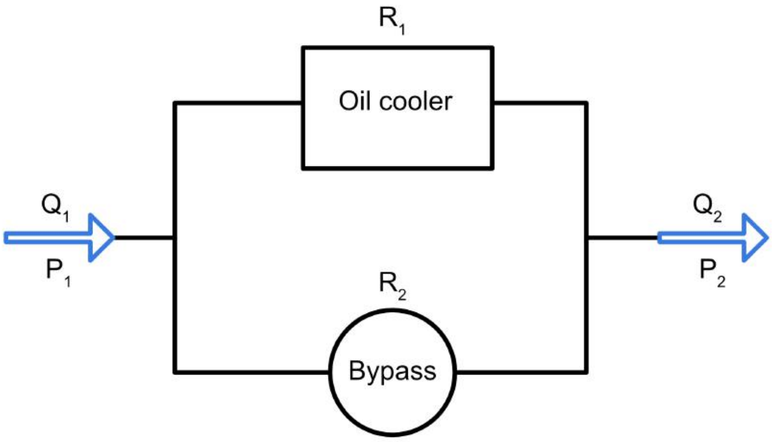


Figure 3.3: Schematic view of the potential flow paths.

To determine the time-to-pressure an assumption is made that the entire volume of the oil system has to be filled up to reach the desired pressure target. Thereby the time can be calculated by dividing the volume with the flow rate of the fluid.

$$t = \frac{V}{Q} \tag{3.3}$$

4| Methodology

4.1 Competitors analysis

A competitor analysis was made to check if any similar solutions had been made prior to this project. An automotive database called A2Mac1 was used to analyze engine designs of other car brands. The focus of the analysis was to find if any other brand had implemented a technical solution that bypasses the oil cooler. A2Mac1 only provides images and comments of the disassembled parts, no drawings or schematic overviews are available. The amount of cars in A2Mac1's catalogue was limited and a total of 60 cars was available to investigate.

A research was done on component level to gather knowledge on what kind of technical solution that could be implemented as a bypass valve. The European Patent Register was used as source to gather information.

4.2 Concept generation

In order to find a technical solution to solve the problem with time-to-pressure, different concepts was needed to be generated and evaluated. Various creative tools have been used to generate as many unique concepts as possible.

The chosen method to generate concepts in a creative way was Brainstorming. This method does not allow any critique while generating ideas, the evaluation is performed afterwards when the generation is completed. To get different approaches for a solution, multiple sessions of brainstorming were performed. The sessions were performed both with and without discussion in order to let each participant come up with as many ideas as possible. The concepts are named K followed by a number.

When sufficient ideas had been generated using the creative method, a systematic method was used to further investigate the potential of the generated concepts. The chosen method was a Morphological matrix. This method divides concepts into sub concepts, allowing them to be combined in different ways and thereby create new concepts.

4.3 Concept evaluation and selection

The process of eliminating and selecting concepts to further evaluate them as final concept contenders is desirable to be done objectively and with a sense of reasonable thinking. Therefore systematic methods, containing matrixes to compare concepts, were performed as evaluation tools.

A Pugh matrix is intended to compare solutions or concepts in relation to each other, terms of how they perform on a number of criteria. The result presents the amount of positive, neutral and negative values that each solution has in relation to the chosen reference. Conclusions can be made whether the solution shall be further evaluated, be eliminated or be analyzed for improvements in worse performing areas.

The Pugh matrix was used to determine if the chosen "base solutions" were suitable to generate concepts from. Two iterations were done in order to cover the whole product-in-production-aspect and the specific function at cold starts.

The first step to evaluate the generated concepts and remove the unfeasible ones was to use an elimination matrix. The matrix had criteria which had to be fulfilled in order for the concept that was evaluated to be considered plausible. The concepts that passed the elimination matrix would get a more detailed evaluation while the concepts which did not fulfill the criteria would be eliminated.

The considered criteria were realizable, space, complexity, robustness and price. Explanations of each criteria can be found in Appendix A. A question mark in the matrix means that further investigation is needed to fully verify if the requirement of the criteria is met.

The next step in the evaluation was to use a Kesselring matrix which is a method where concepts are rated individually to get a score of performance. The criteria are first weighted against each other to give relevance in how important they are for the desired product. The importance is represented in points based on the amount of criteria. Each concept is thereafter judged for every criteria and valued on a scale from one to three. The criteria importance score is multiplied by the judged value and after completion of judging a total value is summed up. The ideal concept has the maximum of points and acts as a reference. Finally a ranking of the concepts is presented. This systematic method delivers a decision basis to consider for which concepts that should further be taken into the development process. The full list of criteria are listed in Appendix A with a short description. The criteria were chosen to cover the full range of aspects that are required for production.

4.4 Concept development

To get a visual clarity of how the concepts would be implemented in the physical environment of an engine they were to be designed in a CAD program. VCC uses the software Catia V5. The latest models of a VEA GEN3 engine was used as base. Iterations of sketching is a common way of proceeding to be able to obtain the imagined and theoretical function of the conceptual design. Simpler calculations are done to verify that mechanical stress and pressure drops were on acceptable levels. This development process of the concepts is necessary to be able to deeper look into detail if the they still are feasible.

4.5 FEM

To verify stress levels and the risk of resonance in critical parts of the concepts a FEM plugin in the CAD program Catia V5 was used. To establish a model with sufficient reliability a certain amount of simplifying had to be done.

To run a FEM simulation a solid 3D-model is needed as a base. The FEM plugin then creates a mesh by dividing the solid model into small tetrahedrons where smaller size tetrahedrons makes a more accurate calculation but it requires more computing power. In order for Catia V5 to generate the simulation the software needs to know the material properties of the model. Catia has a material database with the standard materials of VCC which was used to apply the correct properties to the model.

Constraining the model is important for the simulation to work and to get the desired accuracy of the FEM analysis. The virtual model should be constrained in the same way as the physical part, otherwise there is a large risk that the stresses and deformations will be distributed in an inaccurate way. When the model has been constrained, the loads from for instance seals and the pressure inside the oil channel can be applied. The loads should be applied as they act in reality to ensure an accurate simulation. A model is considered accurate when the output values have converged. The reliability is dependant on the input parameters, the more accurate the input is the more reliable the output becomes. The results of a simulation should always be analyzed to see if the model behaves as predicted. The magnitude of the respective result should also be judged to ensure that they are reasonable.

4.6 Risk analysis - FMEA

Failure Mode Effect Analysis is a tool to value possible risks and the severity level that follows. It enables the engineers and manufacturer to prevent problems before they occur. VCC has their template with a belonging evaluation scale that is developed for the automotive industry. For this project the VCC template and evaluation scale is used.

To cover all potential failures of a concept, a systematic scan is done by choosing part by part, thinking of what could fail. When a potential failure is agreed to be able to happen the potential effects of failure is documented, followed by a value on the severity scale. Thereafter potential causes are listed and also what actions that can be made to prevent the failure, to later on be valued on the occurrence scale. Thinkable detection's are listed and valued, summing up the potential failures in a total value called RPN, Risk Priority Number. An RPN larger than 100 is classified to be a significant characteristic and has to be taken care of with suitable actions and followups, a RPN below 100 is considered approved.

4.7 CFD simulation

To predict the oil flow and pressure losses through the system design of the different bypass concepts, CFD simulations were done. Due to time limitations and lack of software knowledge within the project participants the simulation job was performed by VCC's CAE-team for combustion engines.

The 3D-models were exported from Catia V5 and imported into the CFD-software. Thereafter the CAE engineer coded the model with correct boundary conditions, material properties, pressures and other necessary details. Specific data regarding the oil system was supplied by responsible engineers for respective areas. Due to lack of information regarding the properties of the oil viscosity at temperatures below 20°C the CAE team decided to do all calculations at 20°C because of the knowledge that all properties for oil and flow rates were correct.

During a start of a combustion engine the conditions are changing rapidly regarding temperatures, flow rates, shear stress between the walls and the oil, pressures and revolutions. A simulation of the real conditions is highly complex and requires a lot of time, therefore a steady state condition was chosen to be investigated. The input data is based on real time measurements and is presented in table 4.1.

Table 4.1: Conditions for CFD simulation.

Parameter	**Value**
Flow type	Laminar
Oil Flow rate	37L/min
Oil Pump rpm	1300
Pressure end of geometry	1 bar atm

Figure 4.1 shows an example of a bypass concept that visualizes the channels where the oil is transported. As the model is simplified it considers the cooler to be closed, since the oil always wants to choose the path with least resistance when flowing through the system. The oil flow is calculated from the specifications of the oil pump, which has a displacement of 30cc, and an efficiency by 95%. The outlet port is set to 0 bar which lets the CFD program to calculate an inlet pressure that is needed to be 0 bar at the end of the path. Thereby the pressure loss can be calculated and will be different depending on which concept that is simulated.

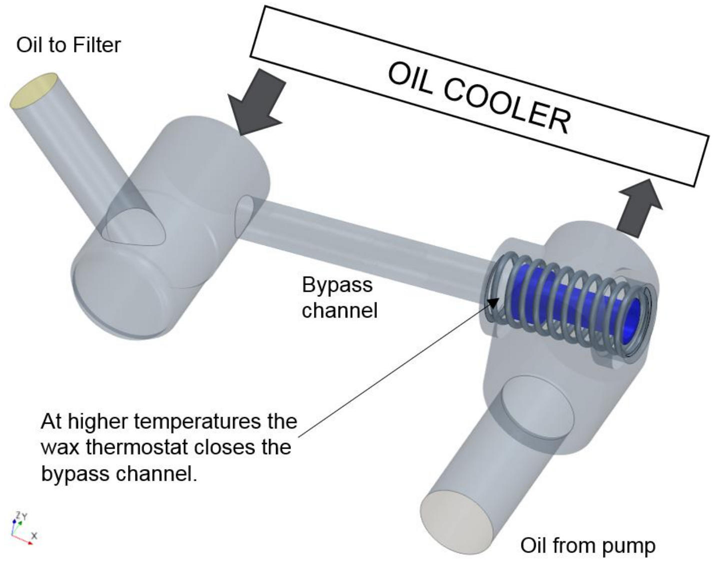


Figure 4.1: Overview of the CFD simulation model with parameters described.

4.8 Prototyping

To get an idea of how the prototype felt in physical form it was 3D-printed. The printer uses an exported file from Catia to build a model, layer by layer, in PLA-plastic (PolyLactic Acid). The printed model was then used as a mock-up to see if it would fit on the oil pan and if there were any issues with the design itself. If there were any problems with the printed model it could be changed before an actual prototype was built.

A drawing of the adapter plate was created from the 3D model in Catia which together with the 3D model was sent to a CNC workshop at VCC. An aluminum prototype was then manufactured using a CNC milling machine. Afterwards the prototype was fitted on a disassembled oil pan to make sure that the geometry was correct.

4.9 Test & verification

All testing and verification was done at Volvo Cars. There is a dedicated engine workshop where mechanics build and prepare engines to be tested in rigs and in vehicle. A wide range of test cells are available, enabling engineers to perform desired tests according to VCC standards. For this project a thermal cell was used to perform cold starts with the engine cooled to a desired temperature of -30°C.

The engine used for this test is a Volvo VEA GEN3 diesel engine. The specific engine had been used in earlier stages of function testing for the VEA GEN3 project. This particular engine was fully prepared for oil system testing with a lot of different measuring equipment, particularly to log temperature and pressure. The signals and data processed in this project is engine speed, oil pressure and oil temperature. The pressure point of interest for the project to analyze when measuring time-to-pressure is the exhaust camshaft channel, shown i figure 4.2. At that point the oil has reached to all internal channels of the oil system.

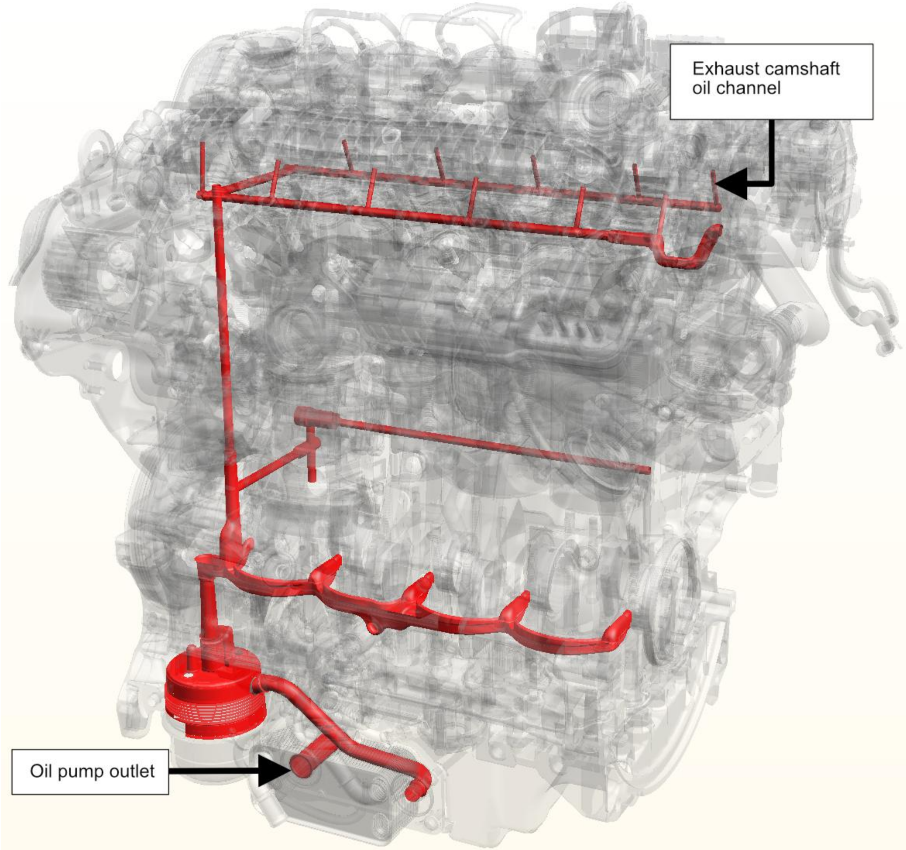


Figure 4.2: Overview of the oil system with marked point of interest when measuring time-to-pressure. The engine in figure is VEA GEN1.

When the baseline runs were performed the engine was brought out of the test cell to mount the prototype produced for this project. Slight modifications to the cooling hoses had to be done due to the new position of the oil cooler. The engine was thereafter installed in the test cell once again, ready to perform new runs.

The test cell with the projects engine installed is shown in figure 4.3. When the engine was completely cooled to the the desired temperature of -30°C, the engine was ready to run start-up procedures. In parallel the data logger was started to collect all measuring data. Because of the engines early development phase the software for the engine management system was not optimized to perfection, causing the engine not to start at the first attempt some times. The system automatically prepares a new start and is thereafter often successful. The varying procedure is causing the log files time axis to be unequal and thereby only delta times are interesting to analyze in the results.

The collected data is used to calculate the time-to-pressure. The condition to determine when to start measuring the time-to-pressure is when the engine speed exceeds 100 rpm, which is the time when the engine starts to crank. The condition to end the measurement of time-to-pressure is when the pressure in the exhaust camshaft oil channel reaches and exceeds 100 kPa. These conditions belong to a VCC standard. A minimum of three runs were performed for each engine build to be able to deliver a mean value and bring enough confidence in the results.

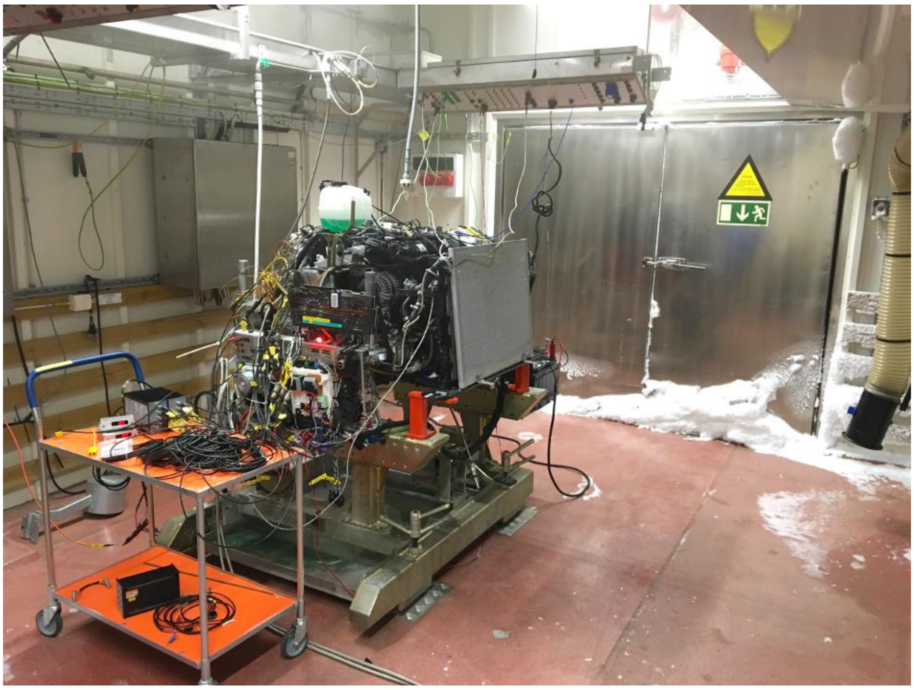


Figure 4.3: Engine rig setup in cold climate chamber at VCC.

5| Results

5.1 Competitors analysis

The analysis of other car manufacturer in A2Mac1 did not show that a bypass over the oil cooler had been done before. Some of the competitors had an oil filter module which was bolted onto the engine. There is a possibility that there were a bypass built into this module, though it was impossible to tell from the pictures provided in the A2Mac1 database.

The research of patents in the European Patent Register gave ideas on how the flow could be distributed through a valve. It also provided understanding on how different types of valves function. No existing patent with a technical solution that bypassed the oil cooler in a combustion engine was found.

5.2 Concept generating

The concept generating process resulted in a large amount of concepts, the complete list of all concepts can be found in appendix A. Brainstorming was the primary creative method and resulted in ten different concepts. Some of them are variants of each other and some may not be fully realizable without further development. The ten concepts shows that there are three plausible areas of implementing a technical solution. Firstly a bypass inside the oil pan with a valve at the outlet of the oil pump with a pipe or a casted channel that leads the oil towards the oil filter. Secondly a valve can be mounted in the oil pan where either casted channels or pipes connect and transport the oil towards the oil filter. Thirdly a valve can be placed between the oil pan and the oil cooler by designing an adapter plate that has internal channels to bypass the oil cooler.

The ten concepts from the creative method, divided into sub-functions, were combined and resulted into 22 additional concepts. To limit the amount of non realizable concepts generated by the morphological matrix some combinations were eliminated in advance. An electrical valve inside of the oil pan was not considered due to the difficulties of having electrical components surrounded by oil as well as sealing issues where the wires require a lead-through into the oil pan.

5.3 Concept evaluation & selection

The different base solutions to control a valve were detected and categorized as pressure difference, thermal dependent and electrical. The overall aspect and the aspect of specific functions in cold start conditions clearly show difference in results for the three solutions. For overall performance the two less complex solutions, pressure and thermal dependent are quite equal meanwhile the electrical solution lacks performance in nine of the total eleven criteria. Pressure and thermal dependent ends up on the same net value.

Secondly the Pugh matrix for performance at cold start shows different results for the three solutions. The electric solution ends up with best performance and is only one net value better than the thermal solution. The results are quite even with slight advantage for the electric in this aspect of evaluation. The results from the two Pugh matrixes ends up in that all three concepts should be further investigated and brought in to concept generating.

To start the process of finding which concepts to bring further into development, an elimination matrix was created. The procedure of the elimination process resulted in an elimination of 24 concepts, leaving 10 for further investigation. The concepts that passed the elimination process were brought into a Kesselring matrix to be further investigated. All criteria were weighted against each other in terms of more, less or equally important. The result of the weighing process, listed in appendix A, shows that criteria with most importance are controllability, risk of contamination, cost and NVH impact. The score scale for each criteria is shown in appendix A. The scores are set after discussion together with supervisor at Volvo Cars, following development standard and price levels. Based on research and discussions with supervisor both the objective and the subjective evaluations were done when the concepts were evaluated for each criteria. The total score, ranking and statistical comparison are presented in appendix A.

The ranking shows that concept S16 has the highest score and without weak points, sketch presented in figure 5.1. K6 is ranked as number two, also without weak points but it has a lower score on controllability due to it's solution with a thermostat instead of a electronic solenoid controlling the bypass valve. The third place in ranking is shared by concept S20 and S21, which both have a score of 143 and have three weak points. Concept S20 and S21 are based on concept K5 which is showed in figure 5.2. Only three points behind the concept K2 is ranked as fourth, shown in figure 5.3

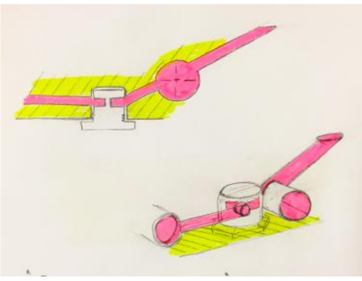


Figure 5.1: Sketch of the concept S16, based on concept K6.

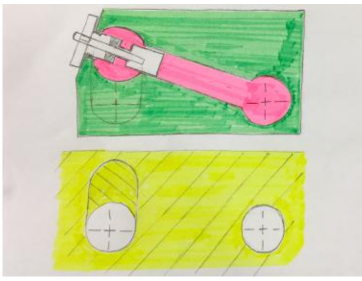


Figure 5.2: Sketch of the concept S20 and S21, based on concept K5.

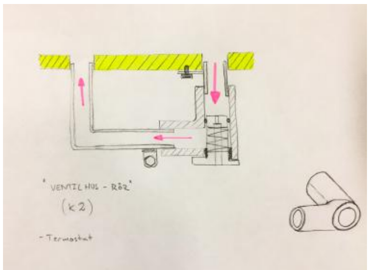


Figure 5.3: Sketch of the concept K2 in early stages of the brainstorming phase.

The outcome from the Kesselring matrix shows the strongest concept contenders and also shows that a thermostatic valve is objectively competitive compared to an electrical solenoid valve. With the total points, ranking and statistics as a decision basis, concept S16, K6, S20, S21, K2 and K5 were chosen for further analysis in FEM. The purpose of taking six concepts into next step of evaluation was the uncertainty of how they would perform in structural stress and resonance simulation. The six concepts are actually only three base concepts that have different details, therefor it was taken as decision to investigate the three base concepts to not miss out on eventual potential.

5.4 3D-modelling

With the concept generating phase completed, the 3D modelling process began. The concepts which were brought to this step in the development were given new names to easier distinguish them from each other. K2 will from now on be called internal pipe, K5 will be called adapter plate and K6 will be called external plug. The different variants of these concepts are grouped together.

5.4.1 Adapter plate

The 3D model of the adapter plate is shown in figure 5.4. The adapter plate is mounted between the oil cooler and the oil pan, designed without interference with the oil pan. In figure 5.5 the adapter plate is shown without the oil cooler. If the bypass valve is open the oil will travel through the internal channel in the adapter plate. This solution requires no design changes to the existing oil pan.

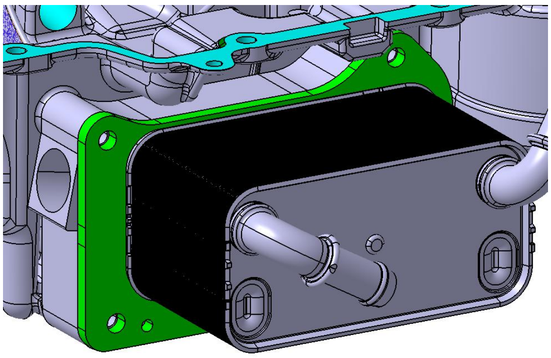


Figure 5.4: 3D-model of the adapter plate with oil cooler.

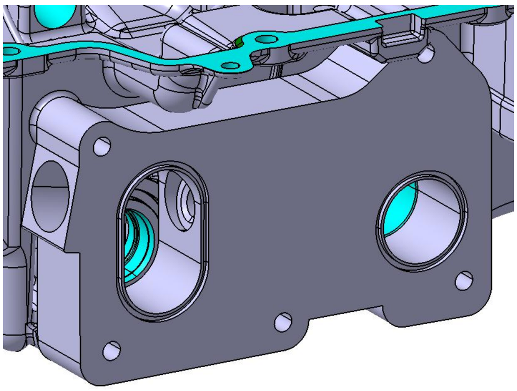


Figure 5.5: 3D-model of the adapter plate on the oil pan.

The section view of the adapter plate is shown in figure 5.6 where the internal channel is visible. When the bypass is open the oil will travel from the oil pump outlet through the bypass channel, and further into the oil pan and towards the oil filter. The direction of the oil flow is shown by arrows in figure 5.6.

Both a thermostat and a solenoid is possible to mount in the extension of the channel, figure 5.7 shows the adapter plate with a thermostat mounted.

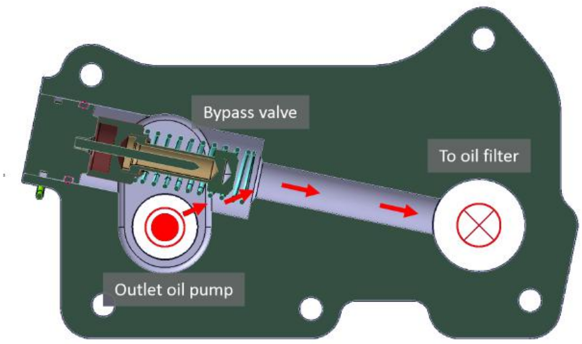


Figure 5.6: Section view of the adapter plate with flow directions.

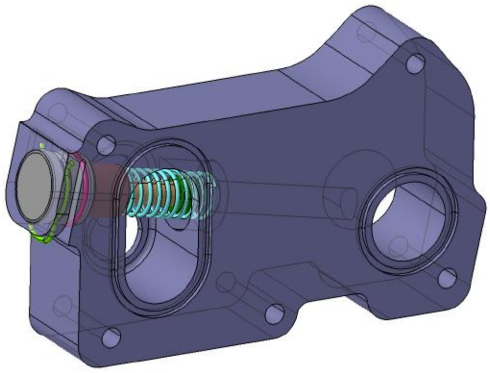


Figure 5.7: Adapter plate assembled with thermostat.

5.4.2 External plug

With the oil cooler removed the changes made to the oil pan is visible, as seen in figure 5.8. The oil will travel through the left inlet hole continuing through the channel which leads to a well where the bypass valve is located. The bypass valve is mounted into the well from the bottom of the oil pan, the mounting hole can be seen in figure 5.9. The well outlet leads to the oil cooler outlet channel. The oil cooler is mounted in the same place as it originally was on the GEN3 oil pan.

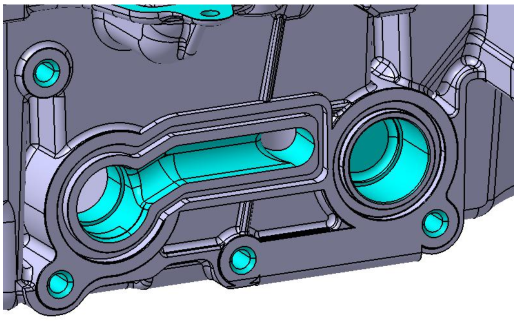


Figure 5.8: The external plug with design changes to the oil pan.

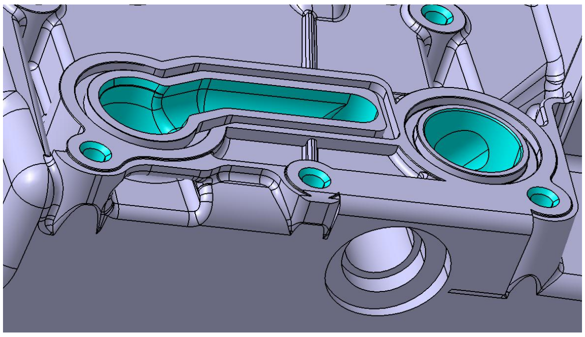


Figure 5.9: Bottom view of oil pan with mounting hole for bypass valve.

A section view is shown in figure 5.10, in this case a thermostat valve is mounted in the well and the arrows showing the direction of the oil flow. When the thermostat is open it allows the oil to leave the well and flow directly towards the oil filter. The inside of the oil pan is shown in figure 5.11. The oil cooler inlet is on the right side of the picture and the well is on the left side.

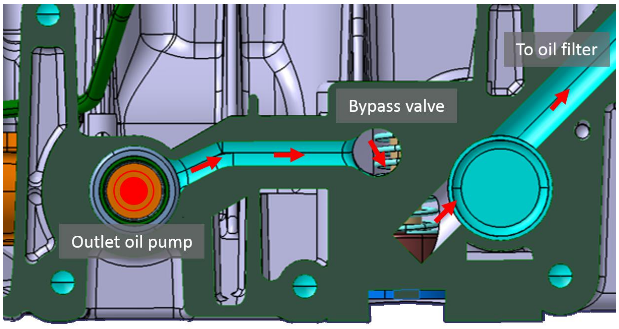


Figure 5.10: Section view of the channels in the oil pan with flow direction.

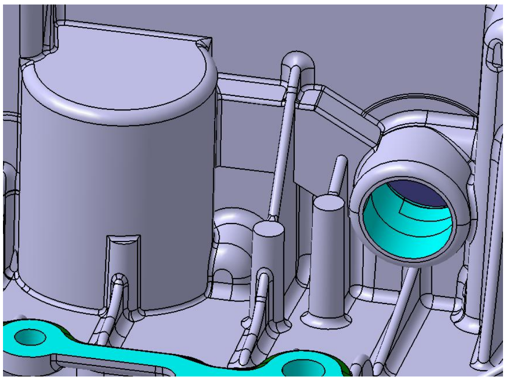


Figure 5.11: The well and the oil cooler inlet, viewed from the inside of the oil pan.

5.4.3 Internal pipe

The assembled 3D model of the internal pipe is shown in figure 5.12. The pipe is located on the inside of the oil pan and it requires no external modifications to the oil pan. The pipe is fastened by screwing it to the oil pan. A section view of the internal pipe is shown in figure 5.12. The flow of the oil is shown by the arrows in the figure 5.13. The well is the same as in the external plug concept and either a thermostat or a solenoid can be placed inside the well to regulate the oil flow.

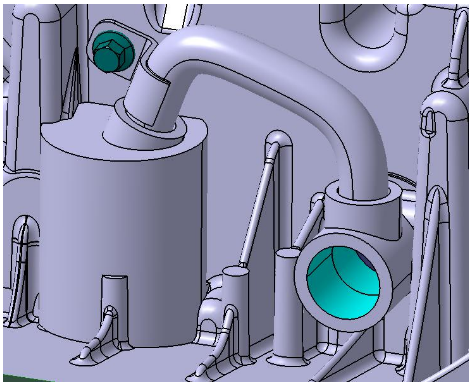


Figure 5.12: 3D-model of the internal pipe solution, viewed inside of the oil pan.

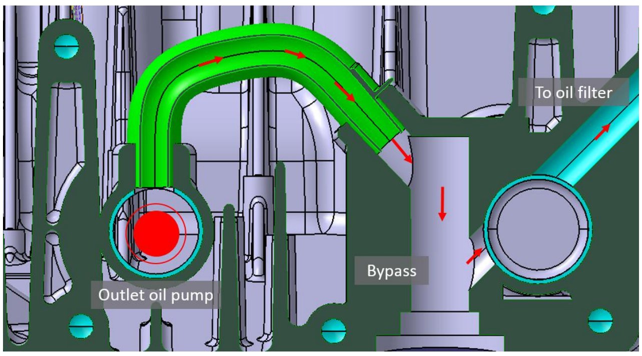


Figure 5.13: Section view of the internal pipe solution with flow direction.

5.5 FEM

Simplified models of the final concept contenders shows that the stress levels are not manageable in all scenarios. The FEM tool therefore acts to eliminate one concept as the results show below.

5.5.1 Simulation of Adapter plate

The adapter plate was simulated to see if there were any displacements that would compromise the seal against either the oil pan or the oil cooler and to determine how large the stress magnitude was. All of the following simulations have been run with a pressure of 20 bar and a force of 800 N on the outlet seal surfaces and 1060 N on the inlet seal surface. The displacement caused from the pressure in the oil system along with the force from the seals against the oil cooler are shown in figure 5.14. The global maximum displacement occurs where the seal groove of the oil cooler inlet is located. The magnitude of the displacement here is 0,006 mm. The displacement is so small that it will not be an issue.

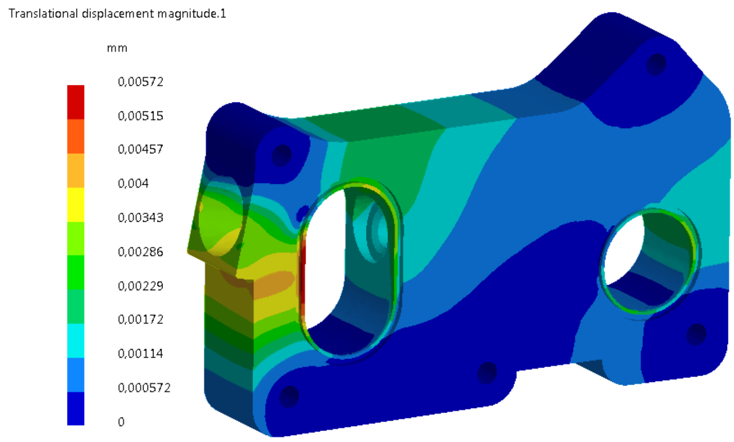


Figure 5.14: Displacement on the oil cooler side of the adapter plate.

The Von Mises stress of the oil cooler side of the adapter plate is shown in figure 5.15. The maximum stress is calculated to be 37 MPa and is located on the same place as the maximum displacement, at the seal groove of the oil cooler inlet. The Von Mises stress located on the oil pan side of the adapter plate is shown in figure 5.16. The surface facing the oil pan has a increased stress level at the area near the large hole for the thermostat, it is calculated to be 19 MPa. Inside of the hole there is a focused point of stress which is calculated to be 32 MPa at maximum. The magnitude of all Von Mises stress levels are far below the yield point of aluminum, which is 160 MPa.

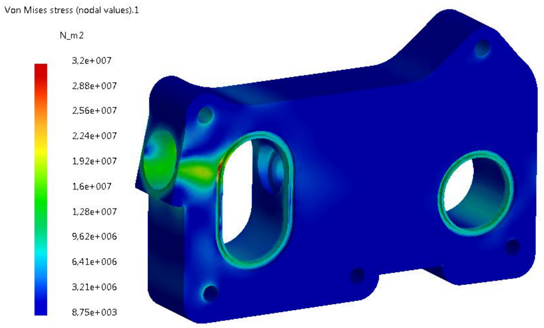


Figure 5.15: Von Mises stress on the oil cooler side of the adapter plate.

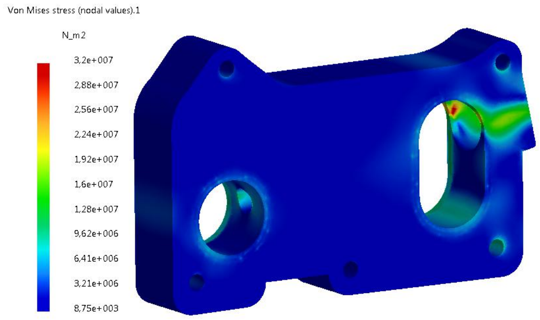


Figure 5.16: Von Mises stress on the oil pan side of the adapter plate.

5.5.2 Simulation of External plug

The critical point of the external plug concept is the increased area of pressure on the oil cooler base plate due to the channel in the oil pan wall. Therefore the oil cooler is to be analyzed. The original seals between oil pan and oil cooler in VEA GEN3 are circular and generates a force of 800N each when compressed. The new oil channel in the oil pan requires a longer sealing and thereby generates an increased force to the oil cooler. The Von Mises stress is shown in figure 5.17. The maximum stress is located in the bottom center screw hole of the plate and it reaches a magnitude of 185 MPa which is slightly above the yield point of aluminum. The sharp edges around the hole can cause inaccurate values, therefor a further investigation has to be done to consider if the base plate will stand the stress levels. Figure 5.18 shows the displacement of the base plate, the maximum displacement is 0.124 mm and located in the center of the plate. The magnitude of the displacement is within the area of tolerance.

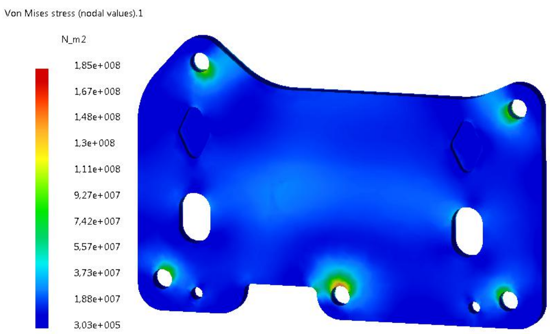


Figure 5.17: Von Mises stress of the mounting plate of the oil cooler.

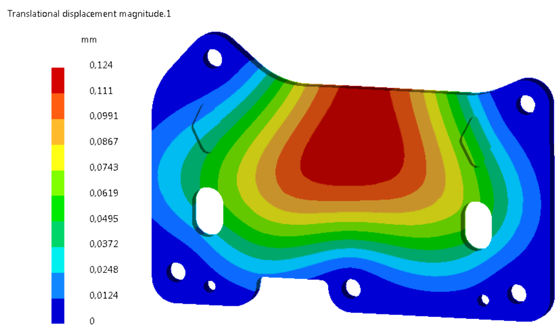


Figure 5.18: Displacement of the mounting plate of the oil cooler.

5.5.3 Simulation of Internal pipe

The pipe was simulated to determine if it would be able to handle the pressure from the oil pump. The following simulations have been run with a pressure of 20 bar.

The displacement of the pipe is shown in figure 5.19. The maximum displacement will occur in the opposite end of the pipe to where the bracket is located. The calculations in Catia showed that a maximum displacement in that point was 1,09 mm.

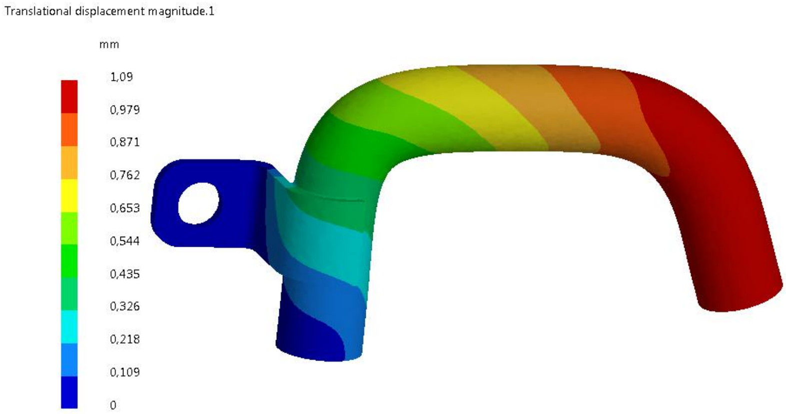


Figure 5.19: Displacement of the pipe.

The Von Mises stress of the pipe is shown in figure 5.20. The stresses with largest magnitude are located where the bracket is attached to the pipe and was calculated in Catia to 1637 MPa. The magnitude is far above the yield point of steel (210 MPa) which therefor would result in a broken pipe. The area of interest around the bracket is shown in figure 5.21. There is a large magnitude of stress where the bracket bends near the screw hole. The stress magnitude is approximately 1400 MPa which indicates that the bracket would easily brake. All results for the internal pipe show that the pipe will not stand the pressure in the oil system, the solution with a pipe was therefore discontinued.

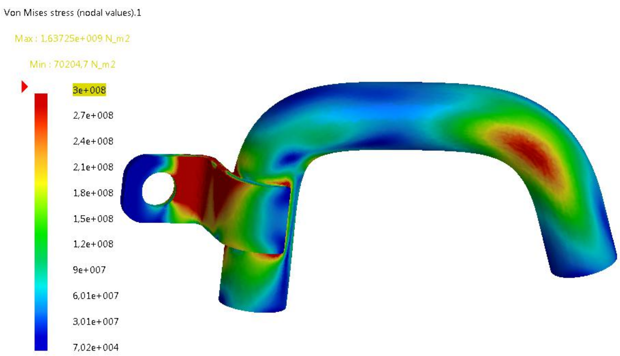


Figure 5.20: Von Mises stress of the pipe.

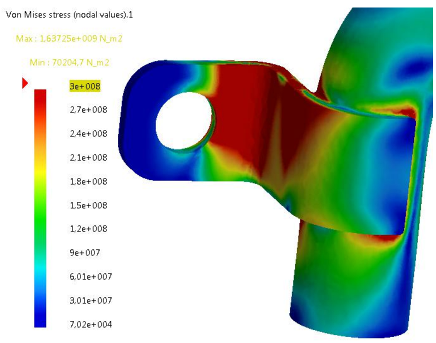


Figure 5.21: Local Von Mises stress where bracket is attached to the pipe.

5.6 Risk analysis - FMEA

An FMEA was performed to prevent the last thinkable failure modes that could occur with respective concept. From the outcome of the earlier FEM analysis the adapter plate with a thermostat, the adapter plate with a solenoid and the external plug were further evaluated in the FMEA. The adapter plate with either a thermostat or a solenoid belong to the same base concept but have different controllability, therefore two separate FMEA were done for them. In appendix B the complete tables are presented with the explaining evaluation scale.

The most critical, potential failure modes are common for the three concepts. Highest risk of failure is if the valve, that opens and closes the oil flow, gets stuck. The worst scenario is if the valve remains open and the engine is working during maximum load, then the oil can be overheated and result in severe damage of the engine. This failure mode has an RPN of 120.

One of the most uncertain risks is contamination on the surfaces of channels and valves. Because of the engine oil that passes through the bypass valve is unfiltered the risk is higher than in other parts of the oil system. Contamination can cause stiction in the valve mechanism or cause bad sealing surfaces which itself can cause internal leakage and thereby decreased cooling of the oil. Observing the thermostatic controlled concepts another critical failure could be if the spring, that preloads the valve, brakes. A small chance could be that small metal pieces can slip through the oil system and destroy internal parts of the engine. A restriction of the oil flow is also to expect if the parts will fall into disadvantageous positions. This failure mode has an RPN of 105

The adapter plate with the solenoid is fairly similar to the adapter plate with a thermostat, it has the same critical risks regarding the valve getting stuck in position. The electrical harness and it's connectors are seen as potential failure modes but are technical solutions with good verification and detection systems. The top failure modes that have been brought by the FMEA are further taken into account for the detailed design and acts as a reminder when freezing the final concept design.

5.7 CFD simulation

As a reference for the following results the pressure drop over the oil cooler is stated to be 4 bar at 20°C and with a flow rate of 37L/min. The pressure drop depends on the flow rate and temperature of the oil, therefor the values below should only be used to compare the different concepts.

The external plug gives a larger pressure drop than the adapter plate. The main cause is that the thermostat in the external plug both restricts the flow and includes a height difference, shown in figure 5.22. The pressure drop is calculated to be 1.245 bar in the external plug. The adapter plate generates a pressure drop of 0.73 bar and as can be seen in figure 5.23 the main restriction source is the path where oil shall flow from the oil pump outlet into the bypass channel.

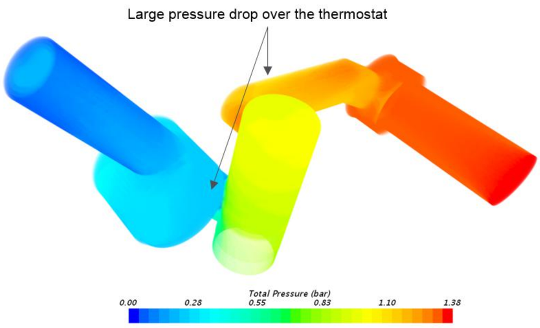


Figure 5.22: Pressure drop over the external plug.

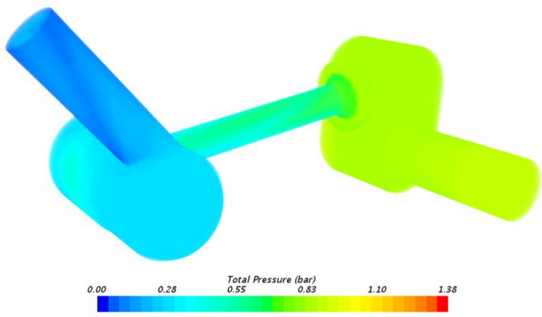


Figure 5.23: Pressure drop over the adapter plate.

Figure 5.24 and figure 5.25 shows a more detailed view of the the distribution of the total pressure. As explained in the method, the inlet pressure varies between the concepts depending on what pressure drop the pump has to overcome to deliver 0 bar pressure at the outlet.

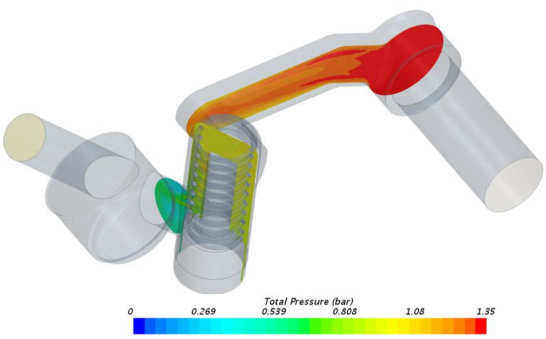


Figure 5.24: Detailed view of the total pressure distribution in the external plug.

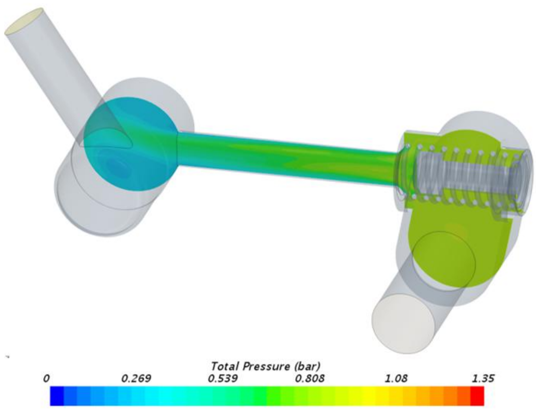


Figure 5.25: Detailed view of the total pressure distribution in the adapter plate.

The flow field is shown in two different parts of the geometry, firstly around the inlet and secondly through the thermostat and towards the outlet. In the first part of the two concepts the velocity magnitudes are similar, approximately 2.5m/s, shown in figure 5.26 and figure 5.27. Both concepts has a good design that does not restrict the flow to the oil cooler when the bypass is closed.

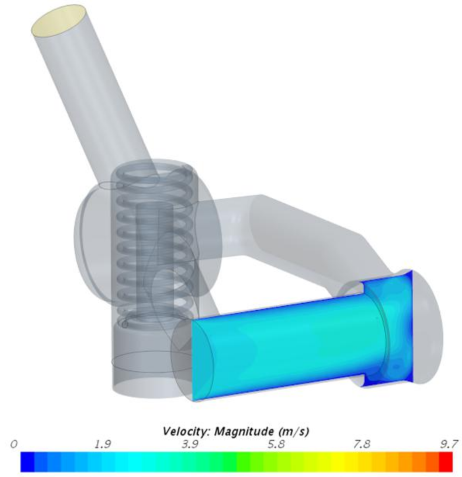


Figure 5.26: Flow field with velocity magnitude in the first part of the geometry in the external plug.

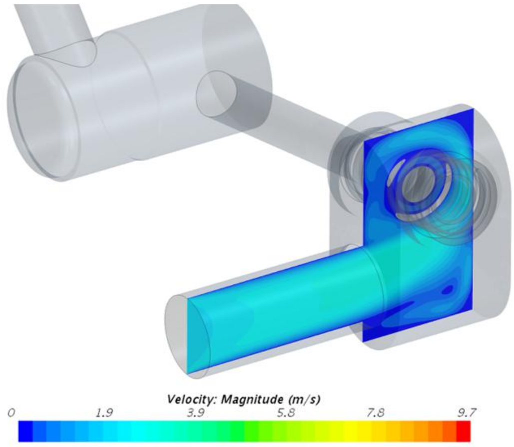


Figure 5.27: Flow field with velocity magnitude in the first part of the geometry in the adapter plate.

The second part of the geometry for respective concept has minor differences were the adapter plate generates a higher velocity through the bypass channel, a magnitude of maximum 9.7 m/s. This is a result of the smaller channel diameter and can be seen in figure 5.29. A higher velocity will increase the friction and thereby increase the pressure drop but also heat the oil at the same time. For the external plug, higher velocities are originated around the passages at the thermostat with a maximum magnitude of 9 m/s, seen in figure 5.28.

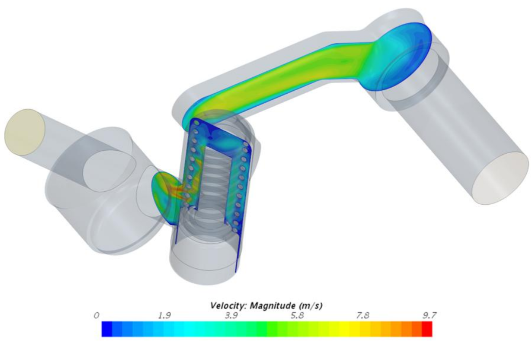


Figure 5.28: Flow field with velocity magnitude in the second part of the geometry in the external plug.

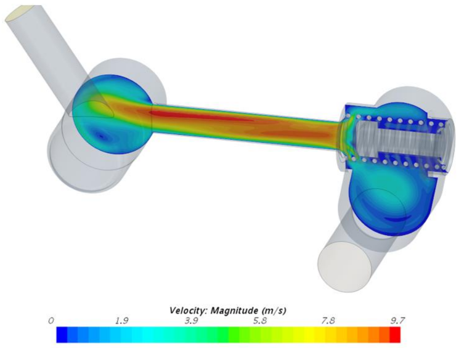


Figure 5.29: Flow field with velocity magnitude in the second part of the geometry in the adapter plate.

As seen in figure 5.30 the flow in the external plug is forced to turn a several times and also change altitude. This generates higher velocity magnitudes and larger pressure drops. According to figure 5.30 most of the oil only passes through a small part of the thermostat chamber. This causes unnecessary turbulence and higher velocities over certain surfaces that could generate cavitational pitting wear.

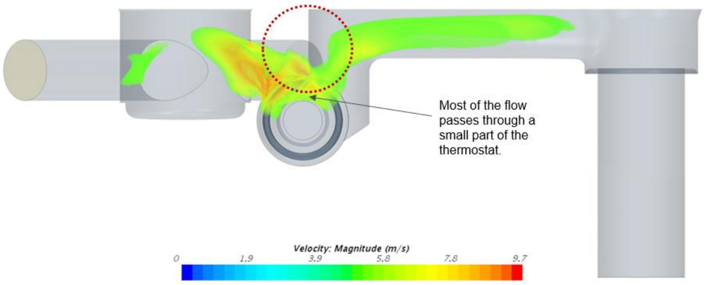


Figure 5.30: Top view of concept K6 showing the flow field through the thermostat.

5.8 Prototyping

To ensure that a test would be performed during the time span of the thesis work the adapter plate was designed to hold a thermostat from a gearbox cooling system. This particular thermostat was presented to the project by the engine cooling department at VCC, after being questioned about what thermostatic components there are in production at the time being. As many parts as possible were reused from the existing gearbox thermostat housing to minimize the amount of parts needed to be manufactured. The geometry of the adapter plate was therefore redesigned to be compatible with the chosen parts, the new design can be viewed in figure 5.31.

The first 3D printed model of the adapter plate, shown in figure 5.31 was tested and did fit on the oil pan, apart from a slight deviation in the bolt pattern which likely was due to the inaccuracy of the 3D printer. The internal thermostat with components did fit inside the adapter plate as intended. A problem with the first version of the prototype was that there were no guiding for the spring which led to unwanted movement of the valve.

Figure 5.31: The 3D printed adapter plate.

In the second version of the adapter plate a spring seat was added, which ensured that the spring would not move when the bypass is open. The bolt holes were also changed to a slightly larger diameter which made sure that the adapter plate would fit on the oil pan. The aluminum prototype of the adapter plate from the CNC workshop matched with the drawing that was provided. The adapter plate was successfully mounted on the oil pan and all the internal parts regarding the thermostat did fit as planned. Figure 5.32 shows the finished adapter plate mounted on the oil pan without the oil cooler.

Figure 5.32: The prototype of the adapter plate fitted on the oil pan.

Figure 5.33 shows the thermostat and the parts needed for it to work. From the left the parts are: spring, thermostat with sealing piston, clips to lock the fastening plug in position and fastening plug with o-ring. The adapter plate with the thermostat mounted is shown in figure 5.34.

Figure 5.33: The internal parts of the adapter plate.

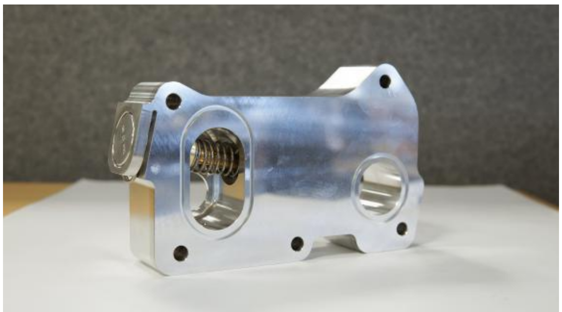


Figure 5.34: Adapter plate with fitted thermostat.

5.9 Test & verification

Cold start tests were performed according to the described method and with full function. No leakage of any fluids was discovered and the climate chamber performed well, cooling the temperature to around -30°C. There existed some difficulties to maintain an exact temperature due to the rather large chamber, the deviation was ±2°C. Three starts were performed with the baseline engine build where two of them were very close to -30°C. The average time-to-pressure for the three baseline runs was 7.8 seconds, the individual times can be seen in table 5.1. The graph in figure 5.35 shows the time lapse of the start up sequence.

Table 5.1: Table of time-to-pressure for baseline engine.

Date of run	**Setup**	**Oil Temp [°C]**	**Time-to-Pressure [sec]**
20180208	GEN3 Baseline	-28.9	7.0
20180213	GEN3 Baseline	-29.5	8.6
20180214	GEN3 Baseline	-29.4	8.3

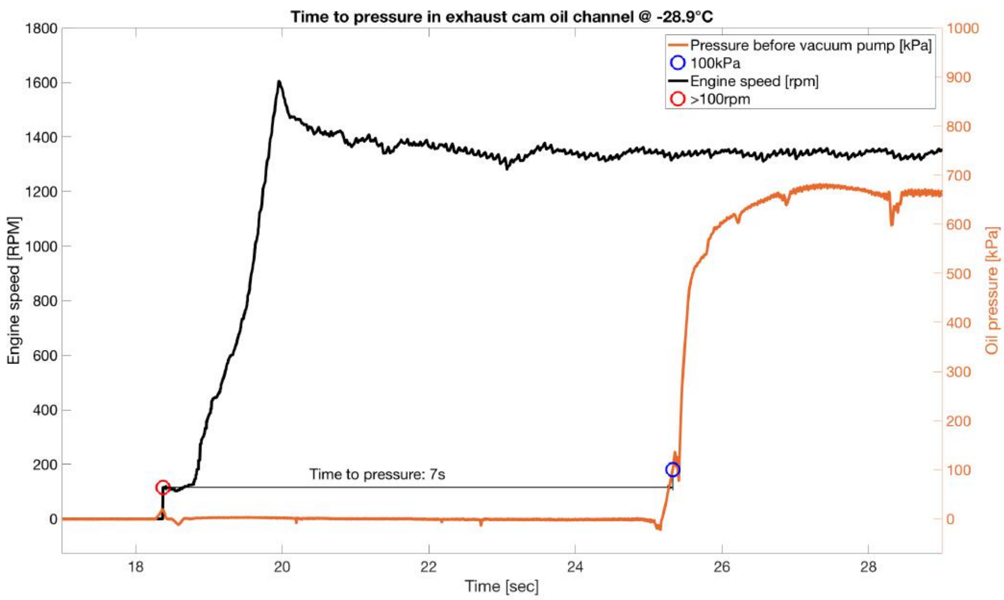


Figure 5.35: Plot of time-to-pressure for base line engine with an oil temperature of 28.9°C.

With the bypass adapter plate installed the results turned out to be significantly improved. The average time-to-pressure when bypassing the oil cooler was now 3.8 seconds. It is a reduction of 51% and 4 seconds in time. The bypass concept thereby meets the requirement, creating pressure at the desired point of measure within 4 seconds from the start of cranking the engine. All time-to-pressure results are listed in table 5.2. The plot in figure 5.36 shows the time-to-pressure and also how the pump is struggling between 13 to 15 seconds on the time axis to control the flow rate. The described struggle, shown as two pressure drops in the graph, is an effect of having a higher flow rate through the bypass channel which leads to quicker response of pressure changes in the system.

Table 5.2: Table of time-to-pressure for engine with bypass installed.

Date of run	Setup	Oil Temp [°C]	Time-to-Pressure [sec]
20180423	GEN3 Bypass	-29.9	4.1
20180424	GEN3 Bypass	-29.8	3.7
20180425	GEN3 Bypass	-28.4	3.5

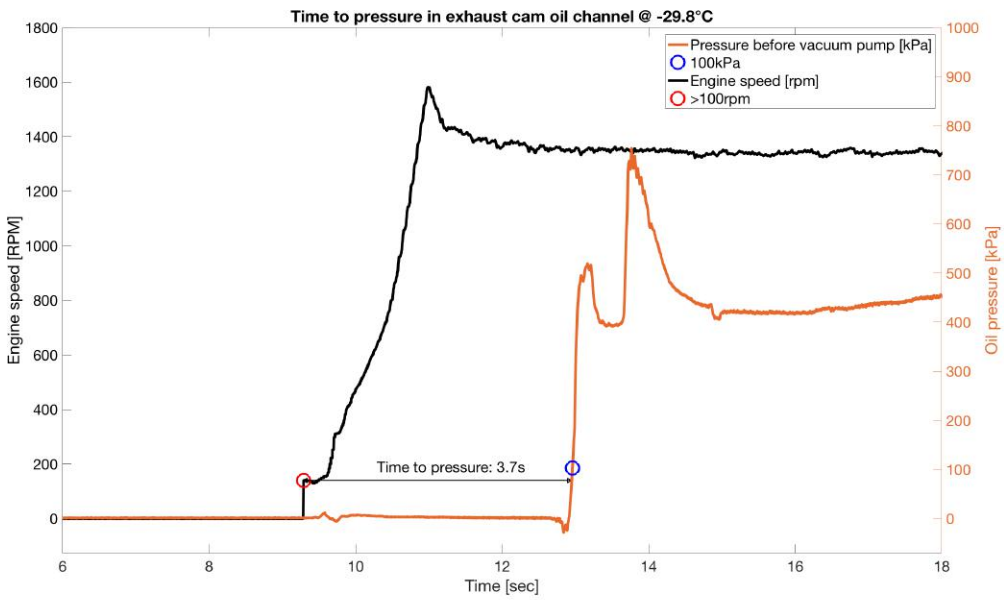


Figure 5.36: Plot of time-to-pressure with bypass valve and with an oil temperature of 29.8°C.

During one of the runs with the bypass prototype the oil temperature was -32.4°C. The result of time-to-pressure is interestingly increased to 5.6 seconds, shown in table 5.3. Even though only one run with this oil temperature was performed it shows the effect of the oil characteristics, drastically increasing the viscosity and thereby making it tougher for the oil to flow through the system. The pressure curve does ramp up more stable and without any overshoot, seen in figure 5.37.

Table 5.3: Table of time-to-pressure for engine with bypass concept cooled to -32.4 °C.

Date of run	Setup	Oil Temp [°C]	Time-to-Pressure [sec]
20180426	GEN3 Bypass	-32.4	5.6

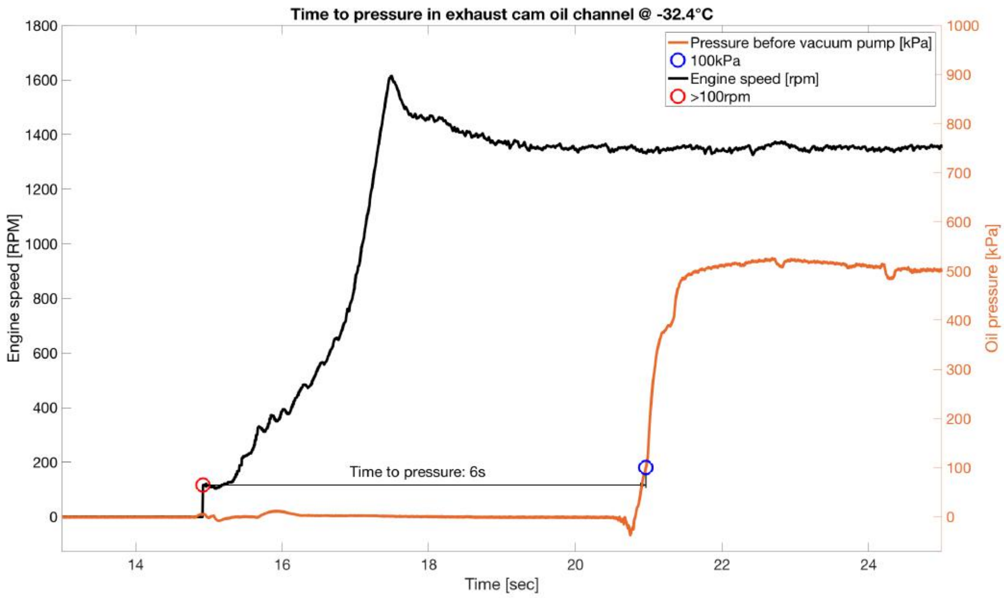


Figure 5.37: Plot of time-to-pressure with bypass valve and with an oil temperature of -32.4°C.

6| Future work

There are several ways to further develop the bypass solution and the project requires more research done before it can be implemented in a engine.

The CFD simulations show that both concepts need optimization to improve the flow rate of the oil and also the path that the oil travels through. Changes to the design and further CFD simulations would be necessary before manufacturing new prototypes. With continuous optimization there are large possibilities to reduce time-to-pressure even further. During testing of the adapter plate concept it was noticed that the heating process of the oil was faster than the baseline engine. CFD simulations also showed that the increased velocity in the bypass channel will generate energy and contribute to heating of the oil. Further investigation regarding the thermal process would be required to determine how big the impact is and how it affects the heating process of the entire engine.

The thermostat valve from the gearbox cooling system that was used when testing the adapter plate is not made for the temperature range of the engine oil. A valve with the correct opening and closing temperatures will need to be designed, tested and verified. There are also possibilities to use other types of valves, such as a solenoid. Further investigations should be done regarding what technical solution of the bypass valve that will suite the future engine in best possible way.

To do a study of the viscosity behaviour at very low temperatures, between 20°C and -30°C, would help to give a better understanding of how the oil flows through the system in such conditions. If that data of the oil is gathered, the CFD models and results from the simulations would be more reliable. The cost aspect of the bypass valve needs to be considered in order to determine if the solution is realizable. The external plug is based on the GEN3 engine and can be optimized further but probably the concept is to be implemented in next generation of engines and thereby a new packaging study has to be made and optimization's thereafter. However, using the concept as a foundation it can provide useful information when designing a new oil system.

7| Conclusion

The problem with long time-to-pressure during cold climate starts is mainly caused by the big pressure drop over the oil cooler. This project investigated and developed a technical solution to bypass the oil cooler and thereby decrease the time-to-pressure. Already when simulating the two final concepts, indications showed an improvement of reduction by approximately 3 bars on the existing pressure loss of 4 bar. The results from the runs with the adapter plate concept mounted on an engine in rig confirmed the improvement which reduced time-to-pressure with 4 seconds to a total of 3.8 seconds.

Interestingly a run with a slightly colder engine oil, -32.4°C, radically increased the time-to-pressure to 5.6 seconds. Being able to understand the oil characteristics better at low temperature ranges would be a great help to establish reliable data when designing the oil system. The results from the performed test runs tend to vary a bit even if the temperature of the oil is nearly identical. If it was possible to verify the cause of the phenomena of irregularity the more comparable the data would have been.

The investigation and test results of this project states the possibilities of implementing the bypass concept in both existing and future engines. The trend of engines continuously downsizing and with kept equal or increased level of performance, there will be a continued big demand of cooling. The results of this project will hopefully inspire VCC to investigate this area of the time-to-pressure solution further and fulfill the requirements in the future development of engines.

References

Connexion Developments, L. (2018). *How does a solenoid valve work.* Retrieved from https://www.solenoid-valves.com/theory/what-is-a-solenoid-valve.php

Exxon Mobil, C. (2018). *How oil filters work.* Retrieved from https://mobiloil.com/en/article/car-maintenance/learn-about-motor-oil-facts/how-an-oil-filter-works

HowStuffWorks. (2018a). *How car cooling systems work.* Retrieved from https://auto.howstuffworks.com/cooling-system8.htm

HowStuffWorks. (2018b). *How does the thermostat in a car's cooling system work?* Retrieved from https://auto.howstuffworks.com/question248.htm

Pennzoil, M. O. (2018). *What is motor oil?* Retrieved from http://www.pennzoil.com/en_us/education/know-your-oil/what-is-motor-oil.html#iframe=L3NvcHVzL3Blbm56b2lsLzIwMTZuZXdzbGV0dGVyLz9sb2NhbGU9ZW5fdXM=

Thermaxx, L. (2018). *Plate frame heat exchangers explained.* Retrieved from https://www.thermaxxjackets.com/plate-and-frame-heat-exchangers-explained/

White, F. M. (2011). *Fluid mechanics.* McGraw-Hill Education.

A| Appendix 1

Table A.1: Matrix of concepts from creative method brainstorming.

K1	This concept had an extension of the drilled channel to the oil filter. The channel met up with another channel that was drilled from the cooler-inlet to form a well. A thermostat was to be inserted from behind the oil cooler into the well and thereby regulating the oil flow.
K2	This concept was meant to be located on the inside of the oil pan. Pipes would lead from the inlet to the oil cooler to a valve housing and then on to the oil cooler outlet. The housing would have a 90 degree bend where a thermostat would be located and thus controlling the oil flow.
K3	The concept was meant to be placed on the inside of the oil pan. It had pipes leading from the oil cooler inlet to the oil cooler outlet via a "banjo-connection" thermostat, which would be screwed into the oil pan.
K4	The concept had a channel milled in the oil pan leading from the oil cooler inlet to the oil cooler outlet. A hole was meant to be drilled from the bottom of the oil pan into the channel where a thermostat would be placed and regulate the oil flow through the bypass.
K5	This concept would be placed between the oil pan and the oil cooler. The wall would have channels to the inlet and outlet of the oil cooler as well as an internal channel which could bypass the oil cooler. A thermostat would be placed in the wall and regulate the oil flow.
K6	The concept would have a channel milled into the oil pan leading from the oil cooler inlet to a well. The well would hold a thermostat inserted from the bottom of the oil pan which could control the oil flow. The outlet of the well would lead to the outlet of the oil cooler.
K7	The concept would have holes drilled from the bottom into the inlet and outlet leading to and from the oil cooler. The holes would lead to a milled channel which would hold an oil flow regulating thermostat. The milled channel would then be covered by a lid.
K8	This concept would have a wall between the oil pan and the oil cooler. The wall would have channels from the oil cooler inlet and outlet leading to a milled channel in the oil pan. The milled channel would have at thermostat screwed into it, regulating the flow.
K9	This concept would have a channel in the bottom of the oil pan which would lead from the inlet of the oil cooler to the outlet. A thermostat would be placed in the channel and a lid would cover the thermostat and seal the channel.
K10	The concept was meant to have a wall placed between the oil cooler and the oil pan. The wall would have a channel leading from the inlet of the oil cooler to the outlet. A thermostat would be placed in the channel, controlling the oil flow. The wall was to be sealed against both the oil cooler and the oil pan.

Table A.2: Morpholocigal matrix presenting the different options that can be combined into new concepts.

	Morphological matrix	Axel & Oskar 2018-01-31			
	Solution / Subfunctions	1	2	3	4
A	Position	Internal	External		
B	Oilchannel	Pipe	Casted channel	Wall between cooler and pan	
C	Control	Spring	Thermal	Electric	
D	Valve	Piston	Damper	Conical plug	Slide action port
E	Assembly	Screw	Lid	Clips	
F					

Table A.3: Results of systematic method.

Combination	Description	Nr
A1-B1-C1-D1-E1	Internal valve housing connected by pipes. Piston regulated by pressure difference.	1
A1-B1-C1-D1-E2	Internal valve housing connected by pipes. Housing closed by lid. Piston reguleted by pressire difference	2
A1-B1-C1-D2-E1/2	Springloaded damper which regulates due to pressure difference	3
A1-B1-C1-D3-E1/2	Internal valve housing connected by pipes. Conical plug regulated by pressure difference.	4
A1-B1-C2-D1-E1	Internal thermosat housing connected by pipes. Piston regulated by thermostat	5
A1-B1-C2-D3-E2	Internal thermostat housing connected by pipes. Conical plug regulated by thermostat	6
A1-B2-C1-D1-E1	Internal casted channel. Piston regulated by pressure difference	7
A1-B2-C1-D1-E2	Internal casted channel. Piston regulated by pressure difference. Channel sealed by lid.	8
A1-B2-C1-D3-E2	Internal casted channel. Conical plug regulated by pressure difference. Channel sealed by lid.	9
A1-B2-C1-D4-E2	Internal casted channel. Slide action gate regulated by pressure difference. Channel sealed by lid.	10
A1-B2-C2-D1-E2	Internal casted channel. Piston regulated by pressure difference. Channel sealed by lid.	11
A2-B1-C1-D1-E1	External springloaded valve. Internal pipe. Piston regulated by pressure difference.	12
A2-B1-C2-D1-E1	External thermostat. Internal pipe. Piston regulated by pressure difference.	13
A2-B2-C1-D1-E1	External springloaded valve. Casted channels. Piston regulated by pressure difference.	14
A2-B2-C2-D1-E1	External thermostat. Casted channels. Piston regulated by thermostat.	15
A2-B2-C3-D1-E1	External electric valve. Casted channels. Piston regulated by voltage.	16
A2-B3-C1-D1-E1	Wall between oilcooler and oilpan with internal channels. Spring loaded valve. Piston regulated by pressure difference.	17
A2-B3-C2-D1-E1	Wall between oilcooler and oilpan with internal channels. Thermostat. Piston regulated by thermostat.	18
A2-B3-C2-D3-E1	Wall between oilcooler and oilpan with internal channels. Thermostat. Conical plug regulated by thermostat.	19
A2-B3-C3-D1-E1	Wall between oilcooler and oilpan with internal channels. Electric valve. Piston regulated by voltage.	20
A2-B3-C3-D3-E1	Wall between oilcooler and oilpan with internal channels. Electrical valve. Conical plug regulated by voltage.	21
A2-B3-C3-D2-E1	Wall between oilcooler and oilpan with internal channels. Electrical damper valve. Damper regulated by voltage.	22
A2-B3-C3-D4-E1	Wall between oilcooler and oilpan with internal channels. Electrical slice action gate. Gate regulated by voltage.	23

Criteria for elimination matrix

- **Realizable**
  The concept can be built and has all the function needed to work.

- **Enough space**
  There is space enough to implement the solution.

- **Complexity**
  That the geometry and parts included not are too complex.

- **Robustness**
  The solution seems robust and does not have any functions that are doubtful to work during the life cycle of the car.

- **Price**
  That the concept does not require materials, parts or processing that is very expensive.

Table A.4: Elimination matrix.

Created	2018-02-01	Modified	2018-06-07			Elimination matrix	
	Requirements to fulfill						
Solution	Realisable	Enough space	Reasonable level of complexity	Fulfills robustness	Reasonable price	Decision	Comment
Creative method							
K1	No					Discard	No flow around the wax body .
K2	Yes	Yes	Yes	Yes	Yes	Keep	Packaging study is required.
K3	No					Discard	Large pressure drop over banjo connection. Attachment of pipe.
K4	No					Discard	Unfeasibe to make a horisontal, internal channel in the wall of oil pan. No flow around the wax body.
K5	Yes	?	Yes	Yes	Yes	Keep	
K6	Yes	Yes	Yes	Yes	Yes	Keep	Review the design o thermostat to get flow around the wax body.
K7	Yes	No				Discard	Oil can get stuck in the bottom. Builds outside the oil pans "hard surface".
K8	Yes	Yes	No			Discard	Too high complexity.
K9	Yes	Yes	No			Discard	Too high complexity, many internal parts.
K10	Yes	Yes	Yes	No		Discard	Requires good sealing.
Systematic method							
S1	Yes	Yes	Yes	Yes	Yes	Keep	Similar to K2 but pressure dependent.
S2	Yes	Yes	No			Discard	Complex with lid, bad accessability for service.
S3	Yes	Yes	No			Discard	Damper is complex and lacks robustness.
S4	Yes	Yes	Yes	Yes	Yes	Keep	Variant of K2 with conical plug.
S5	Yes	Yes	Yes	Yes	Yes	Discard	Same as K3.
S6	?	Yes	Yes	Yes	Yes	Keep	Variant of K2 with conical plug and thermostat. Uncertain about the flow around the wax body.
S7	No					Discard	Flow doesn't really approach in direction towards the spring, thereby no function.
S8	Yes	Yes	No			Discard	Many internal components, requires godd sealing.
S9	Yes	Yes	No			Discard	Many internal components, requires godd sealing.
S10	No					Discard	Too high complexity, many internal parts.
S11	No					Discard	Same as K1 but internal. No flow around the wax body.
S12	Yes	Yes	No			Discard	Advanced geometry, pipe creates complexity and need of many sealings.
S13	Yes	Yes	No			Discard	Advanced geometry, pipe creates complexity and need of many sealings.
S14	Yes	Yes	No			Discard	Same as K6 but with pressure dependent.
S15	Yes	Yes	Yes	Yes	Yes	Discard	Same as K6.
S16	Yes	Yes	Yes	Yes	Yes	Keep	Electric variant of K6.
S17	Yes	No				Discard	Conflicting with the oil filter.
S18	Yes	Yes	Yes	Yes	Yes	Discard	Same as K5.
S19	Yes	Yes	Yes	Yes	Yes	Keep	Variant of K5 with conical plug.
S20	Yes	Yes	Yes	Yes	Yes	Keep	Electrical variant of K5 with piston.
S21	Yes	Yes	Yes	Yes	Yes	Keep	Electrical variant of K5 with conical plug.
S22	Yes	Yes	Nej			Discard	Too high complexity, many internal parts.
S23	Yes	Yes	Nej			Discard	Too high complexity, many internal parts.
S24	Nej					Discard	Combination of K1 & K4. No flow around the wax body.

Criteria Kesselring matrix.

- **Cost**
  The cost indicates how much money each concept will add to the total cost of the engine. Considering the large production volumes that a car manufacturer like Volvo cars have, even the smallest of details are important.

- **Controllability**
  Controllability is to involve the concepts ability to perform the required task. In this project the controllability is judged by how well a piston or valve is moved to block or open the flow of an oil channel.

- **NVH impact**
  Fluid with high velocity and pressure pulsations always have an impact on the structure and will differ depending och the design. In combination with the vibrations created by the engine when running it is likely that components can start to emit noise. Noise and vibrations has a negative impact on the customer satisfaction and especially vibrations can also have a negative impact on the life span of a component.

- **Assembly - level of difficulty**
  The level of difficulty to assemble the concept itself before it shall be mounted on the engine.

- **Internal assembly - number of components**
  The amount of components that has to be assembled internally in the concept to create full function.

- **Service**
  Service of a car is important to be as simple as possible. Depending on if the concepts will need to be serviced and how accessible it is, it will give an approximation of the time to service which indirectly is a cost.

- **Amount of added material**
  The amount of added material that is needed to manufacture the concept, including internal components. If there was to be a solution that only required modification of the original engine, for example creating a oil channel in the oil pan, the amount of material is unchanged.

- **Capability of recycled material**
  The possibility and amount of material that is used from recycled sources for manufacturing and the possibility of recycling the components once again.

- **External assembly - number of components**
  The number of components that are required to assemble the concept externally, either on the inside or on the outside of the engine. Fastening elements are included.

- **Risk of contamination**
  The generated concepts are to be in contact with oil constantly and the oil is mostly unfiltered. Surfaces of metal, rubber and plastic will be covered in oil and there is a risk of contamination that can stay permanent. Contamination can lead to degraded function or in worst case breakdown.

- **Number of sealing surfaces**
  The number of sealing surfaces that either seals the oil from leaking out from the engine or seals internal functions like a valve.

Table A.5: Table of weighting of criteria for Kesselring matrix.

Wheighting of criteria for Kesselring matrix															
Criteria		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**Sum**	**Rank**	**Total wheight**
A	Cost	-	0	0	1	2	2	2	2	2	0	2	13	2	9
B	Controllability	2	-	1	2	2	2	2	2	1	1	2	17	1	11
C	NVH impact	1	0	-	2	2	2	2	2	0	0	1	12	4	8
D	Assembly - level of difficulty	0	0	0	-	1	2	1	1	0	0	0	5	7	4
E	Internal assembly - number of components	0	0	0	0	-	2	1	2	0	0	0	5	7	4
F	Service	0	0	0	0	0	-	0	0	0	0	0	0	11	1
G	Amount of added material	0	0	0	0	0	1	-	2	0	0	0	3	9	3
H	Capability of recycled material	0	0	0	0	0	1	0	-	0	0	0	1	10	2
I	External assembly - number of components	0	0	1	1	1	2	2	2	-	0	0	9	6	6
J	Risk of contamination	0	0	2	2	2	2	2	2	1	-	0	13	2	9
K	Number of sealing surfaces	0	0	0	2	2	2	2	2	0	0	-	10	5	7

Table A.6: Score table for Kesselring matrix.

Intervals of criteria			Comment
Cost	1	High cost (>12€)	Cost of components
	2	Normal (6-12€)	
	3	Low cost (<6€)	
Controllability	1	Pressure	What the valve can be controlled by
	2	Temprature	
	3	Temp. and/or pressure	
NVH Impact	1	High	Amount of components, moving parts, etc.
	2	Average	
	3	Low	
Assembly - level of difficulty	1	Difficult	Difficulty to assemble internal in concept and extarnal on engine
	2	Average	
	3	Easy	
Internal assembly - number of components	1	> 5	Number of parts to be assembled internally in concept
	2	3 - 5	
	3	< 3	
Service	1	Difficult	Difficulty to service. Accessibility, time/cost
	2	Average	
	3	Easy	
Amount of added material	1	Large added amount	How much added material that is required, if any
	2	Small added amount	
	3	Unchanged	
Capability of recycled material	1	None	How much material that come from recycled sources for manufacturing and possibillity of recycling the components once again
	2	Partly	
	3	Largely	
External assembly - number of components	1	> 6	Number of components to assemble concept on engine, fastening elements included
	2	4 - 6	
	3	< 4	
Risk of contamination	1	High	Oil in contact with rubber or plastic can create deposits/accumulations
	2	Average	
	3	Low	
Number of sealing surfaces	1	> 4	Number of moving parts and complexity of those parts
	2	2 - 4	
	3	< 2	

Table A.7: Kesselring matrix.

Bachelor thesis 2018		Kesselring matrix																					
Creators: Oskar Pettersson, Axel Hellsten				Created: 2018-02-05 Edited: 2018-05-07				Page 1															
Criterias		Ideal		K2		K5		K6		S1		S4		S6		S16		S19		S20		S21	
Name	w	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
Cost	9	3	27	2	18	2	18	2	18	2	18	2	18	2	18	2	18	2	18	2	18	2	18
Controllability	11	3	33	2	22	2	22	2	22	1	11	1	11	2	22	3	33	2	22	3	33	3	33
NVH impact	8	3	24	2	16	3	24	3	24	1	8	1	8	1	8	3	24	3	24	3	24	3	24
Assembly - level of difficulty	4	3	12	2	8	3	12	3	12	2	8	2	8	2	8	3	12	3	12	2	8	2	8
Internal assembly - number of components	4	3	12	3	12	1	4	2	8	3	12	3	12	3	12	2	8	1	4	1	4	1	4
Service	1	3	3	1	1	3	3	3	3	1	1	1	1	1	1	3	3	3	3	3	3	3	3
Amount of added material	3	3	9	2	6	1	3	2	6	2	6	2	6	2	6	2	6	1	3	1	3	1	3
Capability of recycled material	2	3	6	2	4	3	6	2	4	2	4	2	4	2	4	2	4	3	6	2	4	2	4
External assembly - number of components	6	3	18	2	12	2	12	3	18	2	12	2	12	2	12	3	18	2	12	2	12	2	12
Risk of contamination	9	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27
Number of sealing surfaces	7	3	21	2	14	1	7	2	14	2	14	2	14	2	14	2	14	1	7	1	7	1	7
Total		33	192	23	140	24	138	27	156	21	121	21	121	22	132	28	167	24	138	23	143	23	143
Rel total		1,00	1,00	0,70	0,73	0,73	0,72	1,17	1,11	0,64	0,63	0,91	0,86	0,92	0,96	1,33	1,38	1,14	1,14	1,05	1,08	0,82	0,86
Average		3,00	17,45	2,09	12,73	2,18	12,55	2,45	14,18	1,91	11,00	1,91	11,00	2,00	12,00	2,55	15,18	2,18	12,55	2,09	13,00	2,09	13,00
Deviation		0,00	8,23	0,33	6,07	0,74	7,42	0,50	6,93	0,50	5,09	0,50	5,09	0,36	6,00	0,50	8,02	0,74	7,42	0,66	9,09	0,66	9,09
Median		3,00	18,00	2,00	12,00	2,00	12,00	2,00	14,00	2,00	11,00	2,00	11,00	2,00	12,00	3,00	14,00	2,00	12,00	2,00	8,00	2,00	8,00
Number of weak points		0		1		3		0		3		3		2		0		3		3		3	
Rank		**REF**		**4**		**5**		**2**		**7**		**7**		**6**		**1**		**5**		**3**		**3**	
Rank (Excel)		REF		5		6		2		9		9		8		1		6		3		3	

B| Appendix 2

Table B.1: FMEA evaluation scale

SEVERITY

Effect	Criteria: Severity of Effect on Product (Customer Effect)	Rank
Failure to Meet Safety and/or Regulatory Requirements	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	9
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).	8
	Degradation of primary function (vehicle operable, but at reduced level of performance).	7
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable).	6
	Degradation of secondary function (vehicle operable, but comfort / convenience functions at reduced level of performance).	5
Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (>75%).	4
	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by many customers (50%).	3
	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%).	2
No effect	No discernible effect	1

OCCURRENCE

Likelihood of Failure	Criteria: Occurrence of cause Design life/reliability of item/vehicle	Rank
Very High	New technology/new design with no history.	10
High	Failure is inevitable with new design, new application, or change in duty cycle/operating conditions.	9
	Failure is likely with new design, new application, or change in duty cycle/operating conditions.	8
	Failure is uncertain with new design, new application, or change in duty cycle/operating conditions.	7
Moderate	Frequent failures associated with similar designs or in design simulation and testing.	6
	Occasional failures associated with similar designs or in design simulation and testing.	5
	Isolated failures associated with similar designs or in design simulation and testing.	4
Low	Only isolated failures associated with almost identical design or in design simulation and testing.	3
	No observed failures associated with almost identical design or in design simulation and testing.	2
Very Low	Failure is eliminated through preventive control.	1

DETECTION

Opportunity for Detection	Criteria: Likelihood of Detection by Design Control	Rank	Likelihood of Detection
No detection opportunity	No current design control; Cannot detect or is not analyzed	10	Almost Impossible
Not likely to detect at any stage	Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g., CAE, FEA, etc.) is not correlated to expected actual operation conditions.	9	Very Remote
Post Design Freeze and prior to launch	Product verification/validation after design freeze and prior to launch with pass/fail testing (Subsystem or system testing with acceptance criteria such as ride and handling, shipping evaluation, etc.).	8	Remote
	Product verification/validation after design freeze and prior to launch with test to failure testing (Subsystem or system testing until failure occurs, testing of system interactions, etc.).	7	Very Low
	Product verification/validation after design freeze and prior to launch with degradation testing (Subsystem or system testing after durability test, e.g., function check).	6	Low
Prior to Design Freeze	Product validation (reliability testing, development validation tests) prior to design freeze using pass/fail testing (e.g., acceptance criteria for performance, function checks, etc.).	5	Moderate
	Product validation (reliability testing, development validation tests) prior to design freeze using test to failure (e.g., until leaks, yields, cracks, etc.).	4	Moderately High
	Product validation (reliability testing, development validation tests) prior to design freeze using degradation testing (e.g., data trends, before/after values, etc.).	3	High
Virtual Analysis – Correlated	Design analysis/detection controls have a strong detection capability. Virtual analysis (e.g., CAE, FEA, etc.) is highly correlated with actual or expected operating conditions prior to design freeze.	2	Very High
Detection not applicable; Failure Prevention	Failure cause or failure mode can not occur because it is fully prevented through design solutions (e.g., proven design standards, best practice or common material, etc.).	1	Almost Certain

FMEA risks shall be prioritized according to below:

1. **Critical Characteristics, CC Sev=9-10**
2. **Significant Characteristics, SC Sev=5-8 Occ=4-10**
3. **RPN ranking Seveverity*Occurrance*Detection**
4. **Other action that FMEA team find suitable**

Table B.2: FMEA for Adapter plate with thermostatic valve.

Number	Item/Object	Function/ Design Intent	Potential Failure mode	Potential Effect(s) of failure	Severity	Potential Cause(s)/Mechanism(s) of failure	Current Design Control: Prevention	Current Design Control: Occurrence	Current Design Control: Detection	Detection	Classification	RPN	Recommended action
	Thermostatic valve	Valve function properly	Locked in open position	Oil overheating due to some oil not passing thruogh oil cooler	7	Mechanism stuck (contamination, damage on piston). Leakeage of wax body	Secure testing of thermostat	4	Monitoring of oil temperature	4		112	Supplier DFMEA (Design FMEA), giving info about functional environment
	Thermostatic valve	Valve funtion properly	Locked in closed position	Longer time-to-pressure	6	Mechanism stuck (contamination, damage on piston)	Secure testing of thermostat	4	Longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5		120	Supplier DFMEA (Design FMEA), giving info about functional environment
	Thermostatic valve	Valve function properly	Broken spring	No control of valve under closing temp. Possible pulsation while in "open mode"	7	Broken spring	Stress calculation and testing	3	Maybe longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5		105	Supplier DFMEA (Design FMEA), giving info about functional environment. Supplier durability test.
	Sealings	Seal oil	Leakage	Loss of oil volume and pressure	8	Damaged by aging, Damaged in assembly, Tolerances, Cracks under pressure	Material analysis, Easy installation, Sufficiant design	3	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		48	Calculation O-ring (compression), choice of material
	Cooler	Sealing	Deformation of oil cooler base plate	Loss of oil volume and pressure	8	Too weak design of oil cooler, new oilchannel with new pressure distrubution over base plate	FEM calculation, testing	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	
	Thermostat plug	Keep thermostat in place and seal	Leakage	Loss of oil volume and pressure	8	Unsifficent sealing, unthreading	Thread locking, sealing dimension	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	
	Piston	Close the bypass channel	Internal leakage	Oil overheating due to some oil not passing thruogh oil cooler	7	Bad sealing surface, piston detaches from thermostat,	Good design and tolerances, secure valve	3	Monitoring of oil temperature,	5		105	Supplier DFMEA (Design FMEA), giving info about functional environment
	Adapter plate/Sump	Corrosion: Corrosion Galvanic / "Spalt" corrosion	Do not fulfil corrosion requirement	External oil leakage	8	Material choice/design	Known material substances.	3	1. LPK (livslängdskorrotionsprov Vagn på Hällered)	3		72	
	Thermostat plug	Corrosion: Corrosion Galvanic / "Spalt" corrosion	Do not fulfil corrosion requirement	External oil leakage	8	Material choice/design	Known material substances.	3	1. LPK	3		72	
	Thermostat/ Adapter plate	Powertrain NVH & Sound Quality: Reduce emitted noise from the engine	Emits noise	Noise	3	Natural frequency	Calculations / simulations / testing	4	1. NVH calculation 2. NVH - rig test 3. NVH - Pass by test 4. NVH complete vehicle	3		36	
	Adapter plate	Service Oil sump should be able to drain out most of the oil at service	Difficult to drain out all oil at service	Bearing wear.	7	Oil trapped in adapter plate	CATIA study	1	1. Engine test	2		14	
	Adapter plate	Manufacturing / Assembly: POKE YOKE	Not POKE YOKE secured	No/restricted oil flow, leakage	8	Wrong Assembly	Asymetric bolt pattern	1	1. Assembly method to be developed together with supplier. 2. P-FMEA at supplier	1		8	

Table B.3: FMEA for Adapter plate with electric valve.

Number	Item/Object	Function/ Design Intent	Potential Failure mode	Potential Effect(s) of failure	Severity	Potential Cause(s)/Mechanism(s) of failure	Current Design Control: Prevention	Occurrence	Current Design Control: Detection	Detection	Classification	RPN	Recommended action
1	Thermostatic valve	Valve function properly	Locked in open position	Oil overheating due to some oil not passing thrugh oil cooler	7	Mechanism stuck (contamination, damage on piston). Leakeage of wax body	Secure testing of thermostat	4	Monitoring of oil temperature	4		112	Supplier DFMEA (Design FMEA), giving info about functional environment
2	Thermostatic valve	Valve funtion properly	Locked in closed position	Longer time-to-pressure	6	Mechanism stuck (contamination, damage on piston)	Secure testing of thermostat	4	Longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5		120	Supplier DFMEA (Design FMEA), giving info about functional environment
3	Thermostatic valve	Valve function properly	Broken spring	No control of valve under closing temp. Possible pulsation while in "open mode"	7	Broken spring	Stress calculation and testing	3	Maybe longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5		105	Supplier DFMEA (Design FMEA), giving info about functional environment. Supplier durability test.
4	Sealings	Seal oil	Leakage	Loss of oil volume and pressure	8	Damaged by aging, Damaged in assembly, Tolerances, Cracks under pressure	Material analysis, Easy installation, Sufficiant design	3	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		48	Calculation O-ring (compression), choice of material
5	Cooler	Sealing	Deformation of oil cooler base plate	Loss of oil volume and pressure	8	Too weak design of oil cooler, new oilchannel with new pressure distrubution over base plate	FEM calculation, testing	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	
6	Thermostat plug	Keep thermostat in place and seal	Leakage	Loss of oil volume and pressure	8	Unsifficent sealing, unthreading	Thread locking, sealing dimension	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	
7	Piston	Close the bypass channel	Internal leakage	Oil overheating due to some oil not passing thrugh oil cooler	7	Bad sealing surface, piston detaches from thermostat,	Good design and tolerances, secure valve	3	Monitoring of oil temperature,	5		105	Supplier DFMEA (Design FMEA), giving info about functional environment
8	Electric wire	Supply electricity and signals to solenoid	No electricity or signal	Longer time-to-pressure (solenoid locked in closed position)	6	Cable breakdown	Correct material choise and proper mounting (vibration and wear)	4	Failed detection of solenoid (monitoring from ECU)	3		72	
9	Connector	Secure electricity and signals to solenoid	No electricity or signal	Longer time-to-pressure (solenoid locked in closed position)	6	Dirt in connector, moisture in connector, disconncected	Sealing, easy and secure mounting	3	Failed detection of solenoid (monitoring from ECU)	3		54	
10	Adapter plate/Sump	Corrosion: Corrosion Galvanic / "Spalt" corrosion	Do not fulfil corrosion requirement	External oil leakage	8	Material choice/design	Known material substances.	3	1. LPK (livslängdskorrotionsprov Vagn på Hällered)	3		72	
11	Thermostat plug	Corrosion: Corrosion Galvanic / "Spalt" corrosion	Do not fulfil corrosion requirement	External oil leakage	8	Material choice/design	Known material substances.	3	1. LPK	3		72	
12	Thermostat/ Adapter plate	Powertrain NVH & Sound Quality: Reduce emitted noise from the engine	Emits noise	Noise	3	Natural frequency	Calculations / simulations / testing	4	1. NVH calculation 2. NVH - rig test 3. NVH - Pass by test 4. NVH complete vehicle	3		36	
13	Adapter plate	Service Oil sump should be able to drain out most of the oil at service	Difficult to drain out all oil at service	Bearing wear.	7	Oil trapped in adapter plate	CATIA study	1	1. Engine test	2		14	
14	Adapter plate	Manufacturing / Assembly: POKE YOKE	Not POKE YOKE secured	No/restricted oil flow, leakage	8	Wrong Assembly	Asymetric bolt pattern	1	1. Assembly method to be developed together with supplier. 2. P-FMEA at supplier	1		8	

Table B.4: FMEA for external concept with thermostatic valve.

Potential Effect(s) of failure	Severity	Potential Cause(s)/Mechanism(s) of failure	Current Design Control: Prevention	Occurrence	Current Design Control: Detection	Detection	Classification	RPN	Recommended action
Oil overheating due to some oil not passing thrugh oil cooler	7	Mechanism stuck (contamination, damage on piston). Leakeage of wax body	Secure testing of thermostat	4	Monitoring of oil temperature	4	SC	112	Supplier DFMEA (Design FMEA), giving info about functional environment
Longer time-to-pressure	6	Mechanism stuck (contamination, damage on piston)	Secure testing of thermostat	4	Longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5	SC	120	Supplier DFMEA (Design FMEA), giving info about functional environment
No control of valve under closing temp. Possible pulsation while in "open mode"	7	Broken spring	Stress calculation and testing	3	Maybe longer time-to-pressure. Pressure sensor that takes into account the data to ECU when cranking?	5		105	
Loss of oil volume and pressure	8	Damaged by aging, Damaged in assembly, Tolerances, Cracks under pressure	Material analysis, Easy installation, Sufficiant design	3	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		48	Calculation O-ring (compression), choice of material
Loss of oil volume and pressure	8	Too weak design of oil cooler, new oilchannel with new pressure distrubution over base plate	FEM calculation, testing	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	
Loss of oil volume and pressure	8	Unsifficent sealing, unthreading	Thread locking, sealing dimension	2	Visual oil leakage, oil monitoring system (oil level), Oil pressure indication	2		32	Calculation O-ring (compression), choice of material
Loss of oil pressure	8	Pipe pops out of the oil pump	Secure pipe position	2	Oil pressure indication	5		80	Design to prevent pipe from popping out
External oil leakage	8	Material choice/design	Known material substances.	3	1. LPK	3		72	Choice of material
Noise	3	Natural frequency	Calculations / simulations / testing	4	1. NVH calculation 2. NVH - rig test 3. NVH - Pass by test 4. NVH complete vehicle	3		36	
Bearing wear.	7	Oil trapped in a"well" and channels	CATIA study	1	1. Engine test	2		14	
External oil leakage	8	Wrong Assembly	Torque monitoring	1	Torque monitoring	1		8	